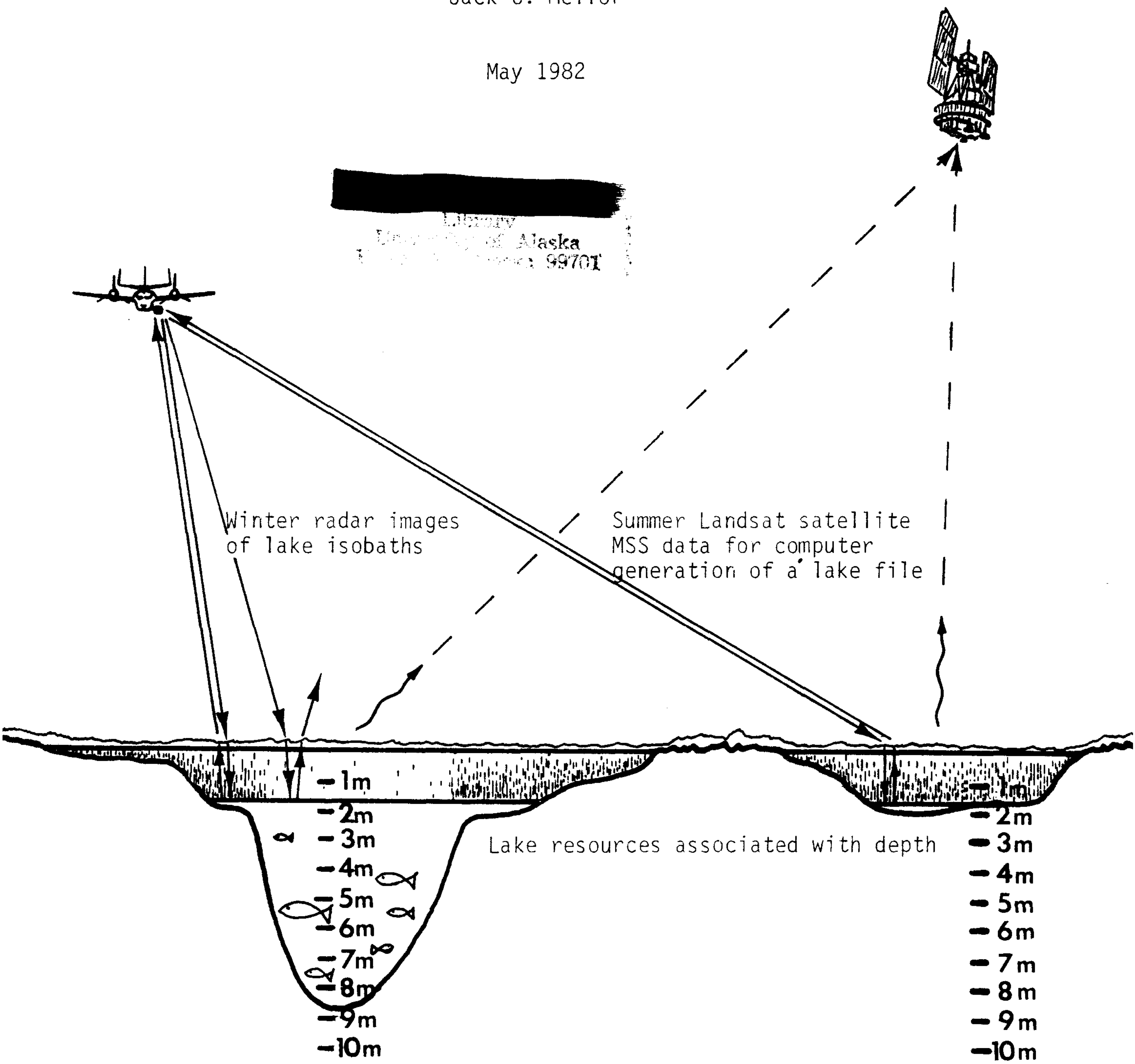
BATHYMETRY OF ALASKAN ARCTIC LAKES: A KEY TO RESOURCE INVENTORY WITH REMOTE-SENSING METHODS

Jack C. Mellor

May 1982

[redacted]



BATHYMETRY OF ALASKAN ARCTIC LAKES:

A KEY TO RESOURCE INVENTORY WITH REMOTE-SENSING METHODS

RECOMMENDED:

P. Jan Cannon

W. S. Reeburgh

Albert E. Belon

C. Peter McRoy

Vera Alexander

Chairman, Advisory Committee

Vera Alexander

Director, Division of Marine Sciences

APPROVED:

K. B. Mather

Vice Chancellor for Research and Advanced Study

April 10, 1982

Date

BATHYMETRY OF ALASKAN ARCTIC LAKES:

A KEY TO RESOURCE INVENTORY WITH REMOTE-SENSING METHODS

A

THESIS

Presented to the Faculty of the

University of Alaska in partial fulfillment

of the requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

Jack C. Mellor, B.S. Biological Oceanography

Fairbanks, Alaska

May 1982

ABSTRACT

Water depth is a major factor in predicting resources associated with tens-of-thousands of uninventoried Alaskan arctic lakes. Lakes were studied for physical, chemical, and biological resources related to water depth in 3 specific areas along a north/south transect extending from Pt. Barrow on the Arctic Ocean to the foothills of the Brooks Range.

Side-Looking Airborne Radar (SLAR) imagery was acquired over the same study transect to investigate its application for determining lake depth. Ice thicknesses, necessary for the interpretation of depth contours from SLAR imagery, were measured along with other parameters in the study lakes throughout the winter 1978-79. This ice-thickness data and sequential SLAR images are used to illustrate a method of contouring water depths in arctic lakes. This is based on changes in intensity of SLAR signal return which define the zone at which ice cover contacts the bottom. This intensity is a function of physical and dielectric properties of the snow, ice, water, bottom substrates, and ice inclusions within these lakes.

A computer program was developed to manipulate Landsat satellite digital data and compile a master file of lakes and their computer-calculated surface features (i.e. area, perimeter, crenulation, and centroid). The master file uniquely identifies each computer catalogued lake by latitude and longitude and stores the calculated features in a data base that can be retrieved for a specified geographic

area. Each lake record also provides storage space for resource data collected outside the computer generated data.

The application of these remote-sensing tools and the knowledge of aquatic resources associated with bathymetry add to our ability for regional inventory, classification, and management of arctic lake resources.

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

CHAPTER III

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

PREFACE

This research was initiated as an attempt to streamline the assessment of aquatic resources in the Arctic. The study was composed of 3 parts: a development of a remote-sensing technique for water-depth data acquisition, limnological survey of the lake constituents by depth, and a development of a data storage and retrieval system by computer manipulation of satellite data.

I describe a remote-sensing method used to identify water-depth contours in Alaskan arctic lakes. Side Looking Airborne Radar (SLAR) images were used in conjunction with ice thickness and lake depth data to dispel any question as to what the uniquely bright SLAR images over arctic lakes portray. I illustrate a method for acquiring 0.5 m lake depth contours down to maximum winter ice thickness depth, utilizing estimated ice thickness in conjunction with SLAR imagery. Growth and variation in lake ice cover is described for the Alaskan arctic for the winter 1978-79.

I address biological, chemical, and physical aquatic parameters as they relate to water depth in the Alaskan arctic. The area of interest extends from the Brooks Range to the Arctic Coast and is large enough to involve a considerable climatic gradient. The list of parameters sampled is extensive, providing ample opportunity for a large matrix of correlations; however, the correlations are primarily restricted to water depth and latitude (i.e. climatic gradient).

As depths and resources within thousands of lake basins are defined, the data must be organized so that they would be retrievable

for future application, for example, resource management and resource identification. I have developed a potential solution, using computer manipulation of digital Landsac satellite data. Landsat computer-compatible tapes were used to produce a master file of lakes uniquely identified on the basis of geographic location. While only a few physical lake features, such as area and perimeter, can be quantified from the Landsat digital data, the significant aspect is the creation of a lake file that is geographically referenced, creating an efficient storage and retrieval system for aquatic resource parameters.

I thank a number of people who assisted in or encouraged me in this work. David Schmidt and John O'Brien identified and counted my zooplankton samples at the University of Kansas. Terri Robus with Northern Testing Labs and Tom Hare in the Bureau of Land Management (BLM) sorted and identified benthic invertebrates. Pat Reynolds, BLM, identified vascular vegetation. Margaret Billington, Tom Chapman, and Dan McCorkle, University of Alaska, assisted with chemical analysis of water samples. Drs. Vera Alexander and Bob Barsdate, University of Alaska, participated in summer limnological sampling. Special thanks are due Morna Seifert for programming and assisting in the development of lake file concepts. Other University of Alaska computer analysts and the computer facility personnel were both helpful and understanding. The author is grateful for encouragement provided by Willy F. Weeks, CRREL, and John Santora, BLM/NPR-A project manager. My committee (V. Alexander, C. P. McRoy, W. Reeburgh, J. Cannon, and A. Belon) provided a vital clearinghouse that by challenging my ideas brought clarity and organization to the final product.

SLAR imagery was acquired through a BLM/U.S. Army interagency support agreement. Members of the U.S. Army 172nd Military Intelligence Detachment Aerial Surveillance (MIDAS), 222 Aviation Battalion, Ft. Wainwright, Alaska, and especially Tom Spinelli, were diligent in attempts to produce the desired SLAR products.

Funding for support of this research has been from both the Bureau of Land Management (BLM) and the Department of Energy (DOE). BLM provided most of the logistic support for my summer and winter field work. BLM also contracted for the acquisition of SLAR imagery and has employed me as limnologist for the National Petroleum Reserve in Alaska throughout this research effort. DOE has supported laboratory analysis, computer programming, procurement of instrumentation, publication, and some field work through a grant to the University of Alaska (Project EY-76-506-2229, Task Order #10).

CHAPTER I

INTRODUCTION TO REGIONAL AQUATIC RESOURCE INVENTORY

THE PROBLEM

The Alaskan Arctic Coastal Plain is covered with tens-of-thousands of lakes and ponds. A few lakes and ponds, primarily those near the Naval Arctic Research Laboratory (NARL) and Point Barrow, have been studied extensively (Hobbie 1973 and 1980). Little to no regional inventory or comprehensive lake surveys have been done across the Arctic Coastal Plain. No lake-specific data are available for the vast majority of Arctic Coastal Plain lakes.

This dissertation revolves around 2 hypotheses. 1) Regional ice thicknesses in combination with Side-Looking Airborne Radar (SLAR) images can be used to provide some lake bathymetry. 2) Lake resources are associated with bathymetry and can be assessed using regional SLAR images. Verification of both hypotheses furnishes an efficient means for Alaskan arctic lake resource inventory.

Remote-sensing tools and limnological surveys are investigated concurrently in this dissertation to determine the feasibility of accomplishing regional inventory of Alaskan Arctic Coastal Plain lakes. The remote-sensing tools are Side-Looking Airborne Radar (SLAR) from fixed wing aircraft and Multispectral Scanner data from a satellite. The limnological surveys include physical, chemical, and biological measurements.

A significant factor stimulating my interest in lake bathymetry was Side-Looking Airborne Radar (SLAR) imagery that was acquired over Arctic Coastal Plain lakes in April and May 1974 (Sellman et al. 1975a). During my residence at NARL, Barrow, I became aware of the use of SLAR images to observe sea ice. Some SLAR data was also acquired over arctic lakes contiguous to the sea ice under study in the Arctic Ocean. The images taken over ice covered arctic lakes were different from images that had been acquired over ice covered lakes in other areas in the contiguous United States. The images of many arctic lakes had a dark perimeter and a bright interior. Ground verification of these images by Weeks et al. (1978) indicated that the dark areas occurred where ice was frozen to the lake bottom while the bright areas occurred where water existed beneath the ice. The SLAR images of nonarctic lakes do not have white centers even though water exists beneath an ice cover. As I formulated my first hypothesis considering the prospects and potential advantages of SLAR as a tool to assist in regional lake depth inventory, I discussed the value of sequential SLAR image acquisition coupled with simultaneous lake verification with Dr. Weeks, who was supportive of the study concept.

If lake depths could be determined with an economical remote-sensing tool, would they be a valuable aid in aquatic resource inventory? This question led to the second supporting hypothesis suggesting that Arctic Coastal Plain aquatic resources are intimately linked to small differences in water depth which can be sensed remotely.

Surface water on the Arctic Coastal Plain exists in a delicate balance hinged upon little precipitation that becomes trapped at the surface by a nonporous permafrost layer. Little evaporation occurs due to 9 months of ice cover, and runoff is minimal because of little terrain relief. The water bodies are typically shallow (2-3 m). Since ice forms to 2 m thickness by mid-winter, the aquatic nature and biotic function of these basins is influenced by ice growth throughout all or a major portion of each of these basins. The fact that aquatic resources are limited to shallow depths and are influenced by ice that reaches to or near the lake bottom, led me to consider how extensively lake resources, properties, and/or constituents might be associated with lake bathymetry.

Multispectral Scanner (MSS) data from the Landsat satellite were used to develop a method of creating a lake data file for storing, classifying, and retrieving the multitude of data created by the regional inventory methods hypothesized above.

Several studies relating to regional water availability and approaches to water and aquatic resources management have been completed on the Alaskan North Slope (Greenwood and Murphy 1972, Furniss and Ward 1975, Wilson et al. 1977). Each study suggested that information gaps exist in water use conflicts (i.e. fish, wildlife, human inhabitants, and industry) and knowledge of water availability (e.g. where and how much water may be used without adversely affecting the environment). Greenwood and Murphy suggest that large-scale ecological studies aimed at establishing important areas for preservation could provide ecological evaluation maps. The maps would be useful to planners for choosing one site or community over another for alteration. The aquatic ecosystems must be defined and inventoried before the "maps" are made. This dissertation describes an investigation of several methods that define, relate, and inventory aquatic ecosystem components that might aid in producing regional ecological evaluation maps economically.

The results of this dissertation both verify the hypotheses and exhibit the potential use of these data collection methods for inventory, classification, and management of the resources associated with Alaskan arctic lakes.

THE APPROACH

Because of the enormous area of interest and the tens-of-thousands of lakes involved, the size of the area and the number of lakes to be studied were reduced by a systematic, rational approach. Remote-sensing and limnological sampling of the study lakes were necessary on a year-round basis. A single straight flight line simplified SLAR acquisition and transected climatic and geomorphological variations needed to delineate the effects of these changes in lake characteristics across the broad region of study. Each lake chosen for study was accessible by fixed-wing aircraft on floats during the summer and ski equipped aircraft in the winter. Finally, the lakes chosen for study represented the full range of water depths within each area of study. This enabled investigation of the resources and constituents associated with lake bathymetry, and the study of the potential for SLAR imagery to resolve that bathymetry.

THE STUDY AREAS AND LAKES

Study Transect

The area chosen for study was a north/south transect across the Alaskan arctic (Figure 1). It incorporated 3 physiographic provinces: the Arctic Coastal Plain, Arctic Foothills, and Brooks Range. The dimensions of the transect were selected to define an area within which both SLAR imagery and limnological samples could be acquired over a climatic gradient. The transect is 25 km wide to accommodate the width of SLAR imagery and also provides a swath with adequate lake diversity from which to select study lakes of varying depth. The transect is 350 km long and extends from Point Barrow in the north to Howard Pass in the Brooks Range in the south. The northern half of the transect contains 150 km of Arctic Coastal Plain with very densely packed lakes and terrestrial elevations not exceeding 91 m above sea level. The lake numbers diminish rapidly as terrestrial elevations increase where the southern half of the transect enters the foothills. The rolling foothills evolve into 1220 m peaks of the Brooks Range at the southern end of the transect.

The marine environment affects coastal freshwaters at the northern end of the transect. The summer fog belt screens out solar radiation

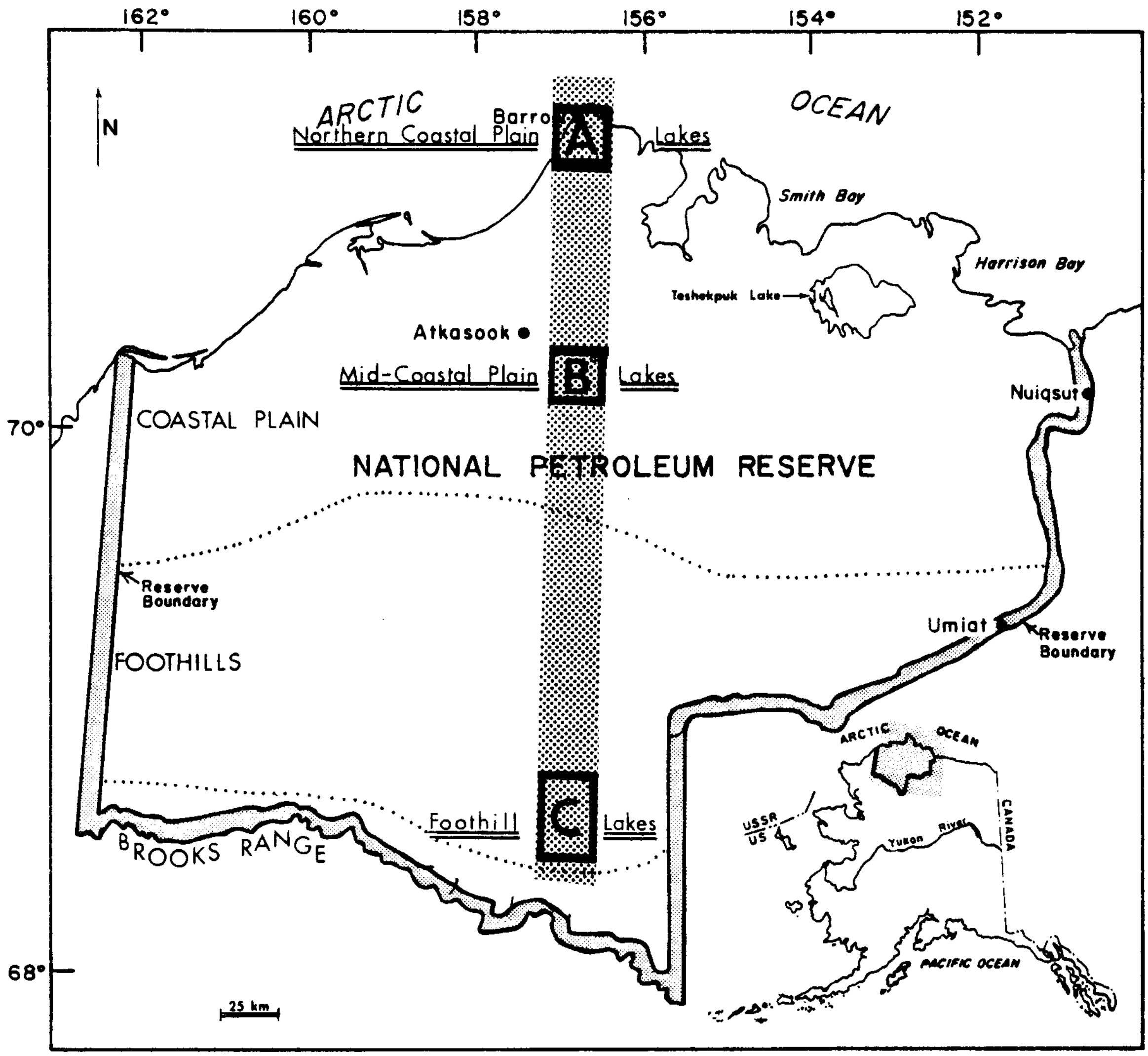


Fig. 1. Study areas within transect used for acquisition of lake and SLAR data.

and keeps temperatures low along the coast. The ice covered Arctic Ocean and the prevailing onshore winds also make coastal summer temperatures cooler than those inland. Less frequent offshore winds disperse fog, but the fog returns rapidly during periods of calm and the more frequent onshore winds. Sea salts contaminate lakes near the coast. As one travels seaward along the transect, lakes generally become larger in surface area, shallower in depth, higher in conductivity (chloride ion concentration) and are often turbid. Holmquist (1975), Sloan (1977), Mellor et al. (1978), and Reynolds et al. (1979) have completed lake surveys showing these trends, in addition to data presented here.

The 3 Study Lakes within each of 3 Study Areas

Three lakes were selected within each of the study areas A, B, and C (Figure 1). Each lake was selected on the basis of maximum basin depth. The deepest lake at each study area called No. 1 was 3 m or more deep. The mid-depth lake called No. 2, typifying most thaw lakes, was close to 2 m deep. The shallow lake or pond called No. 3 was approximately 1 m or less deep. The location and major characteristics for each of the 9 study lakes are listed in Table 1.

Lake Isobaths

Isobaths depicting basin characteristics are shown in Figures 2-10.

Table 1. Study lake locations and characteristics.

LAKE NO.	NAME	LATITUDE	LONGITUDE	MAX. DEPTH (m)	SURFACE AREA (ha)	LENGTH (km)	WIDTH (km)	FISH	DEFINITIVE OR CHANNELIZED INLET	DEFINITIVE OR CHANNELIZED OUTLET
	NORTHERN COASTAL PLAIN LAKES									
A-1	Imikpuk	71°20.2'	156°39.1'	3.1	62	1.0	0.7			*
A-2	Ikroavik	71°13.9'	156°37.9'	2.1	514	4.0	1.5	*		*
A-3	West Twin	71°16.5'	156°29.5'	1.2	127	1.9	0.8			
	MID-COASTAL PLAIN LAKES									
B-1		70°22.9'	156°23.4'	11.5	217	2.0	1.5	*		*
B-2		70°23.2'	156°28.0'	1.9	106	1.6	1.0			*
B-3		70°18.3'	156°25.8'	0.45	∿ 1	0.16	0.09			
	FOOTHILL LAKES									
C-1	Betty	68°28.6'	156°29.5'	6.8	137	2.0	1.0	*	*	*
C-2		68°27.9'	156°44.5'	2.0	77	1.3	0.9			
C-3	Smith Mountain	68°45.0'	156°21.5'	1.1	10	0.6	0.25			

*Observed Present.

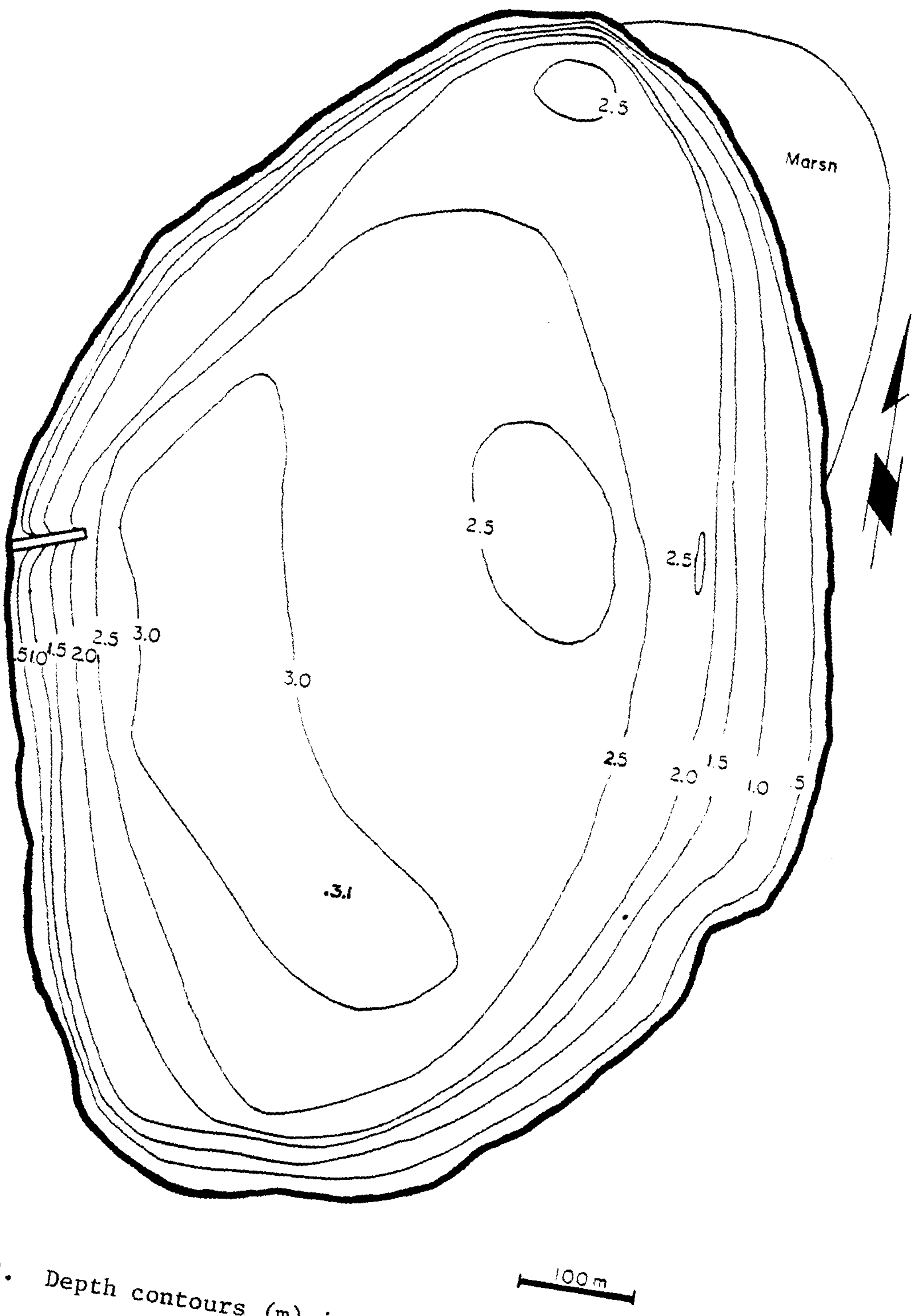


Fig. 2. Depth contours (m) in Lake A-1, Imikpuk.

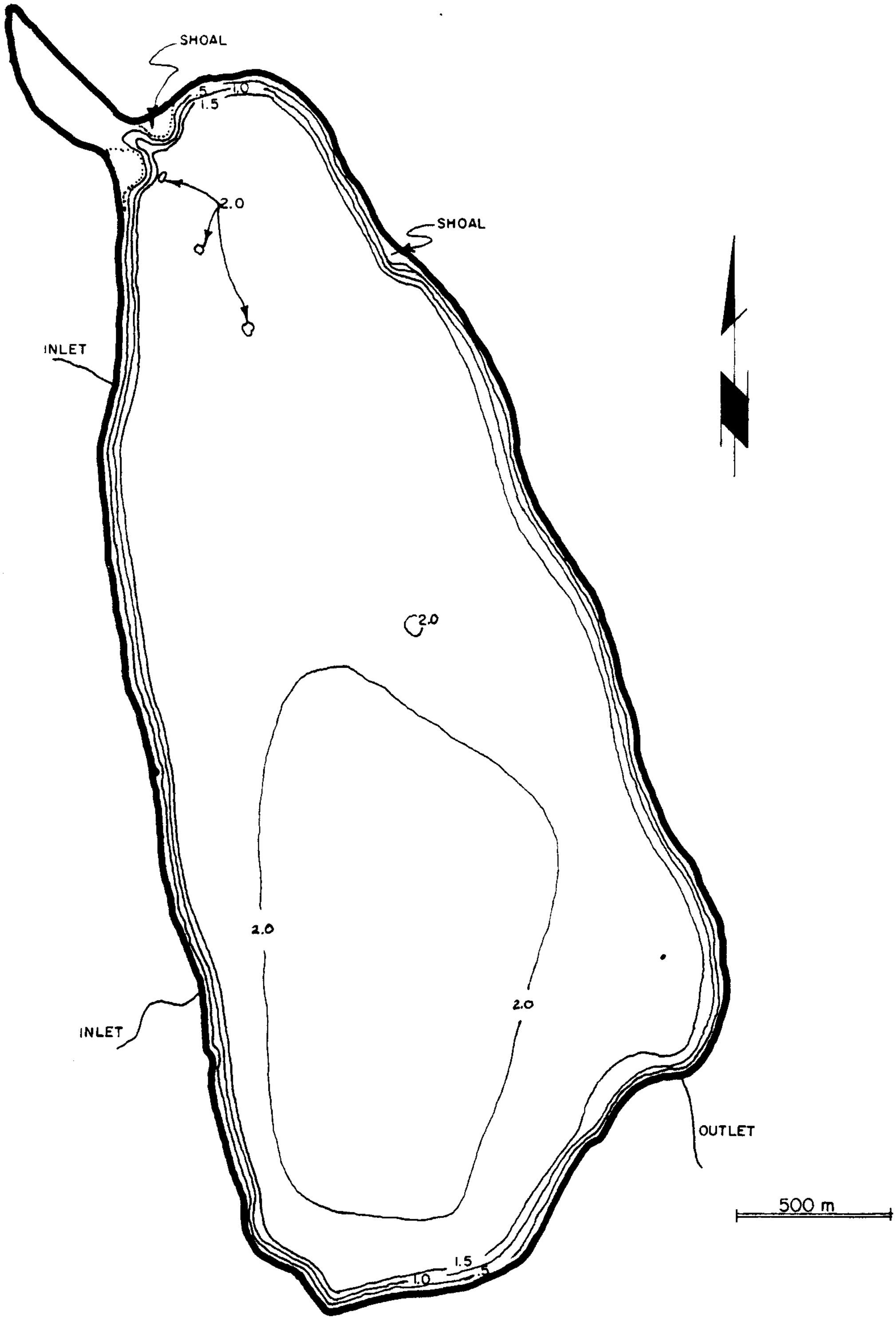


Fig. 3. Depth contours (m) in Lake A-2, Ikroavik.

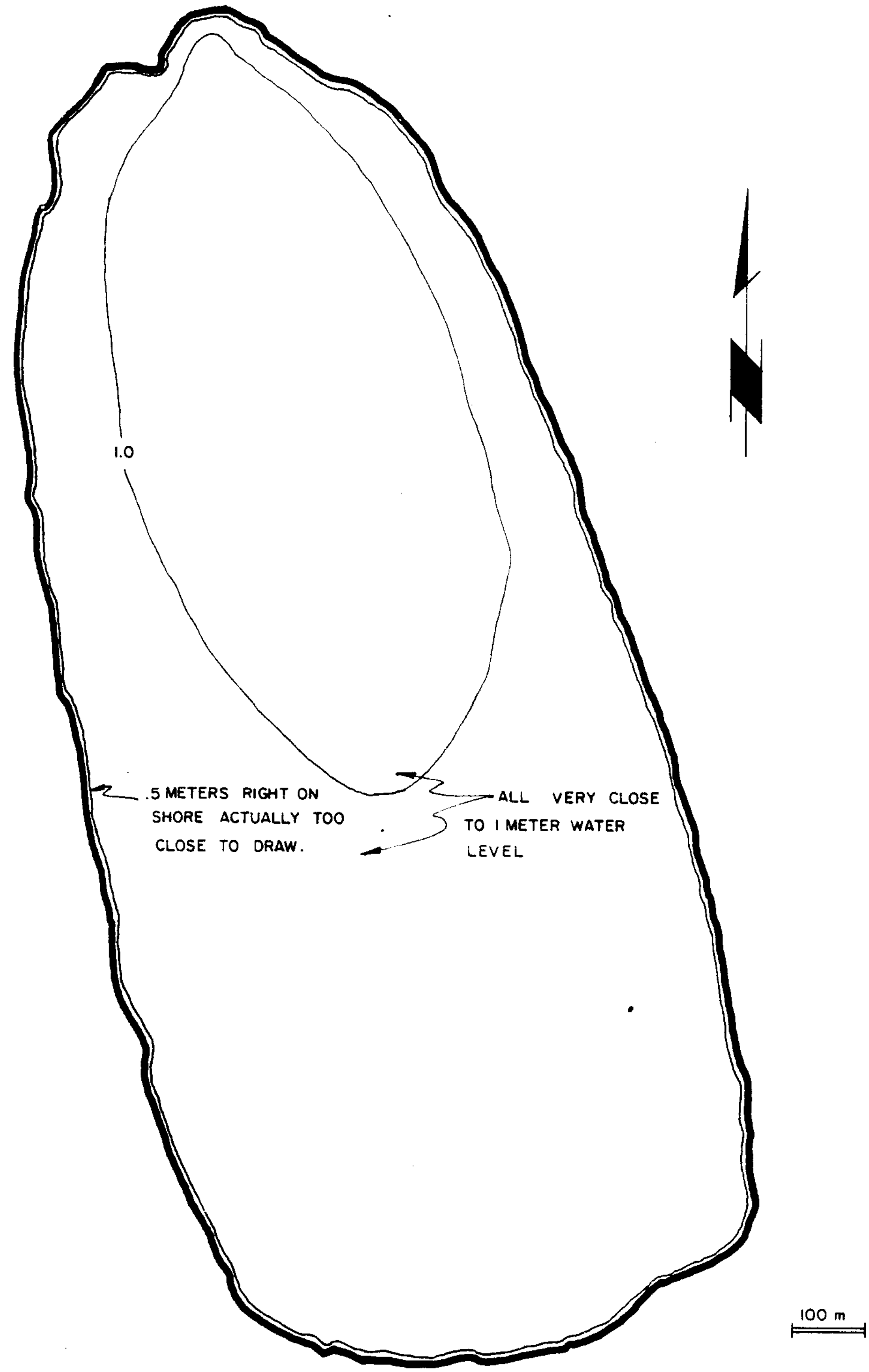


Fig. 4. Depth contours (m) in Lake A-3, West Twin.

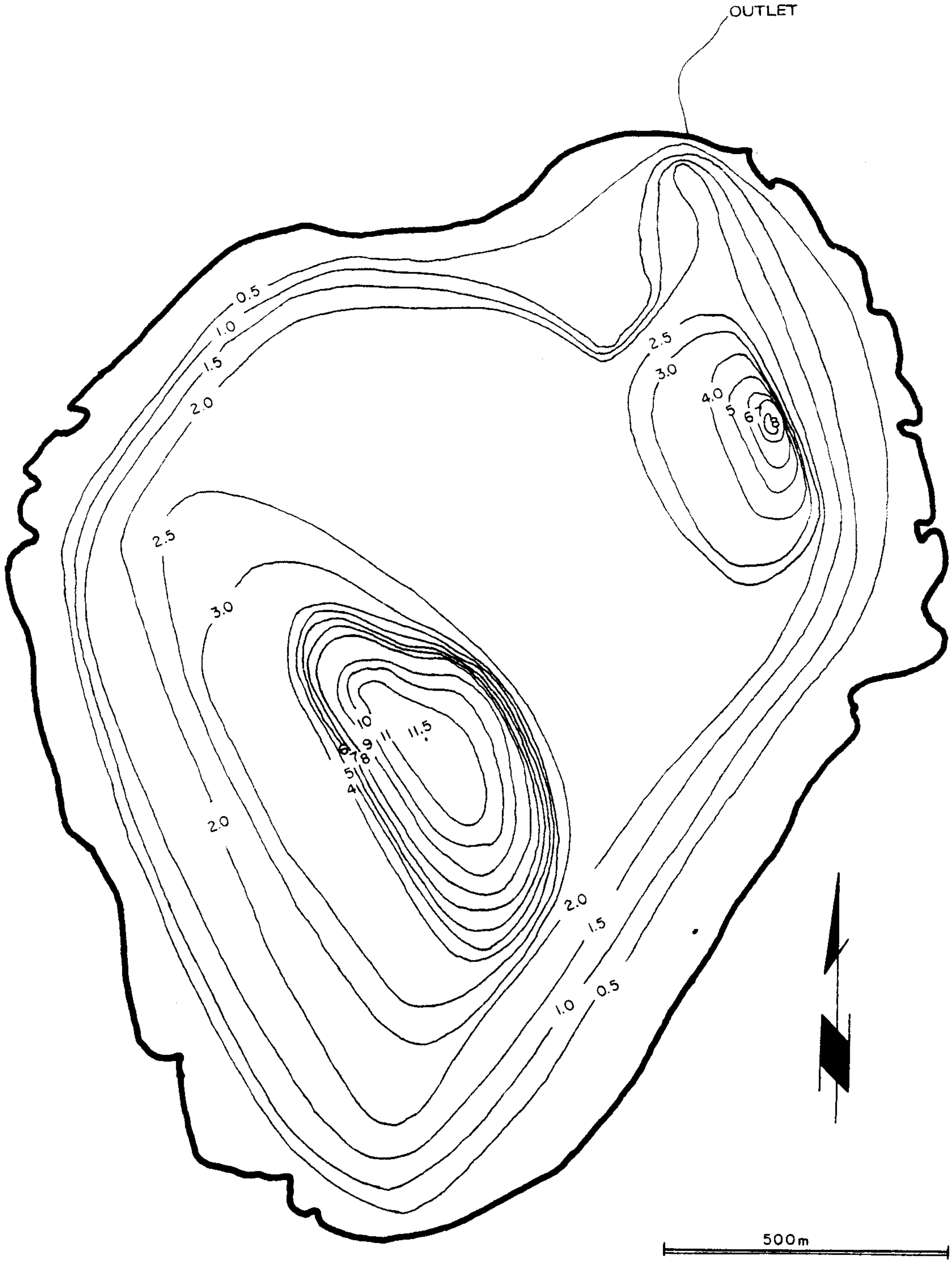


Fig. 5. Depth contours (m) in Lake B-1.

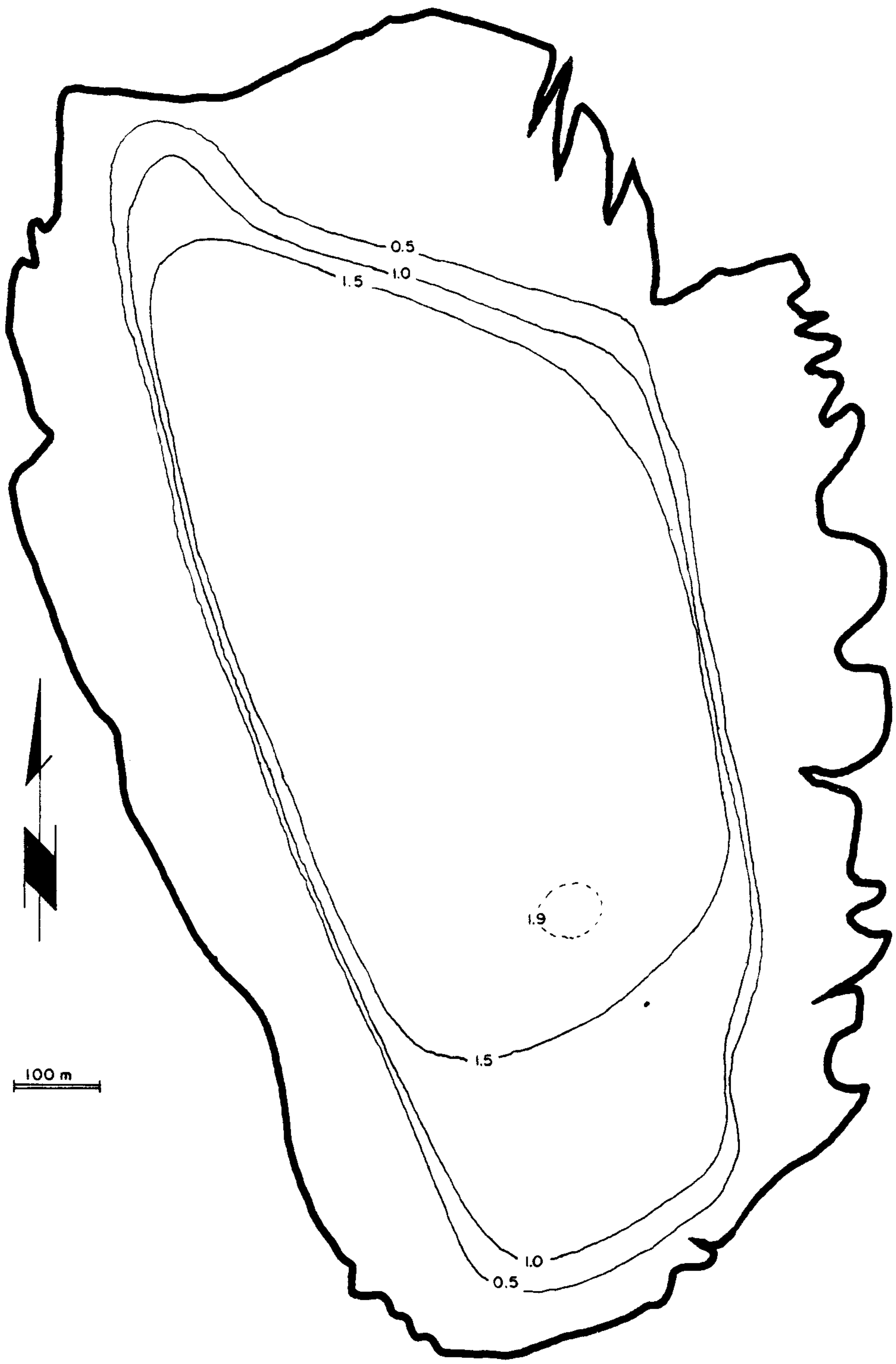


Fig. 6. Depth contours (m) in Lake B-2.

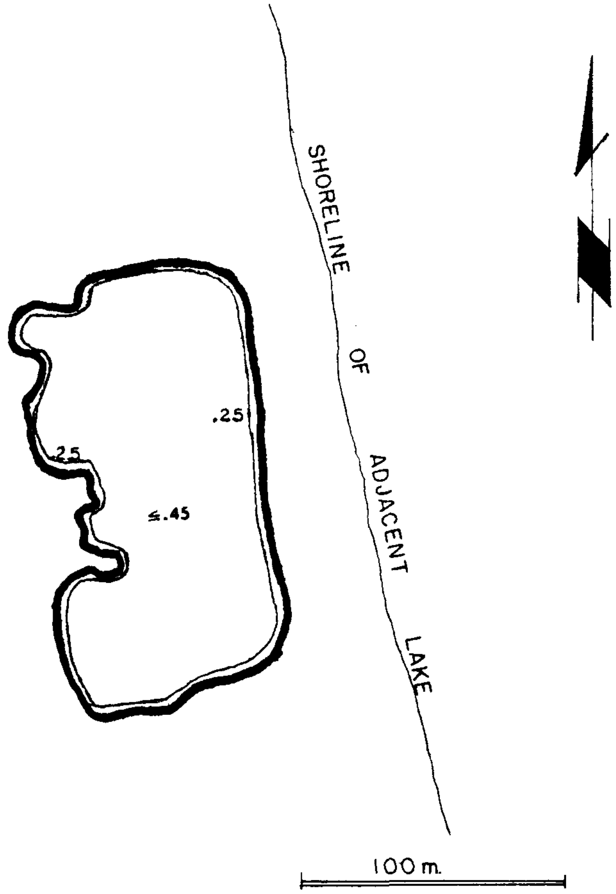


Fig. 7. Depth contour (m) in Pond B-3.

Fig. 8. Depth contours (m) in Lake C-1, Betty.

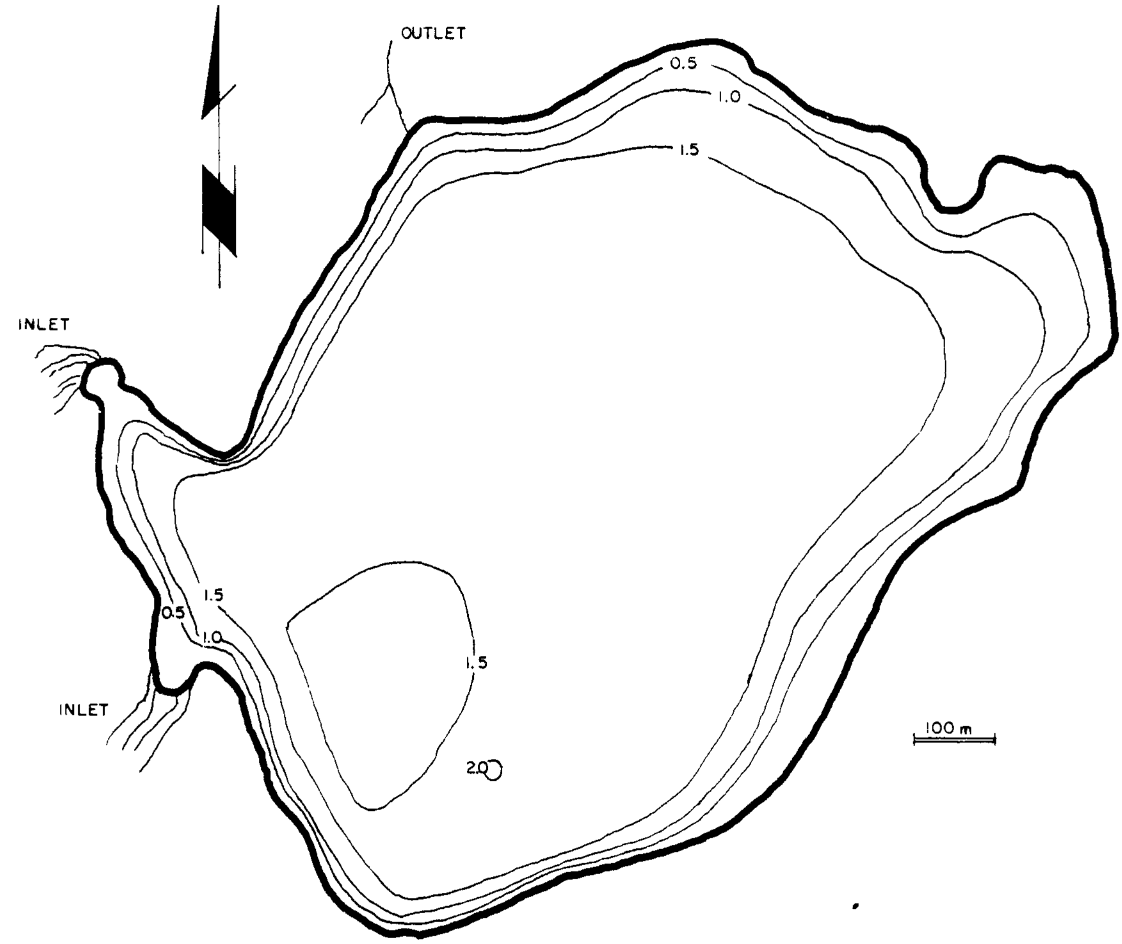


Fig. 9. Depth contours (m) in Lake C-2.

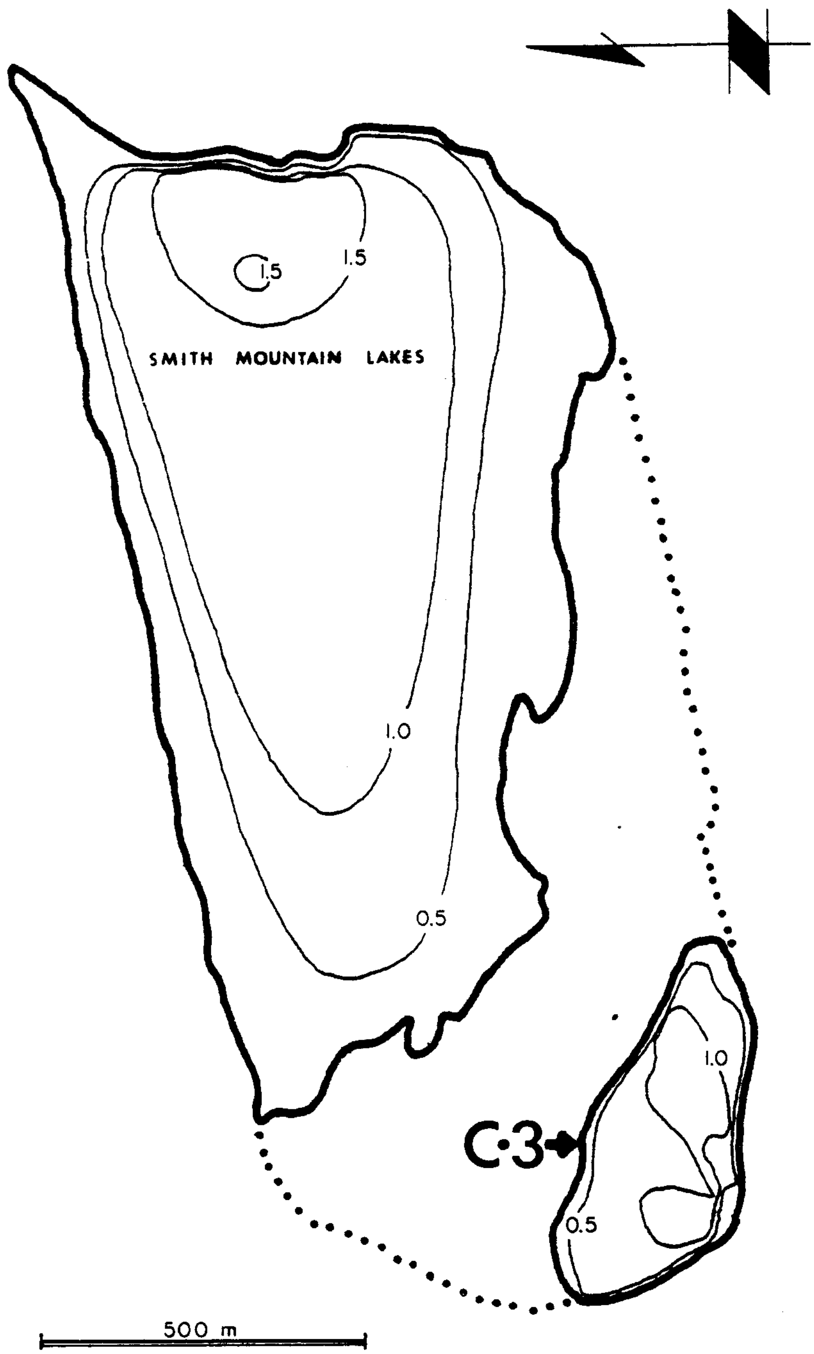


Fig. 10. Depth contours (m) in Lake C-3.

Study Area A - Northern Coastal Plain

Study Area A is within the northern end of the study transect (Figure 1) near Barrow Village. The map (Figure 11) shows the 3 lakes, nearby population centers, the Arctic Ocean, and surrounding lakes and ponds. The area is influenced on 3 sides by the polar marine environment. The climate is generally cold and windy with a nearly continuous overcast. Weaver (1966) reported the following climatic conditions for the Barrow area. Summer temperatures seldom exceed 5°C, while winter temperatures below -40°C are infrequent. The average annual temperature is -12.4°C. July is usually the warmest month, with a mean of 4°C, and February the coldest, with a mean of -28°C. Mean annual wind speed is 5.4 m per second. Maximum cloud cover occurs in the late summer and fall, with minimums in the spring. Average annual cloud cover is 6.8 tenths, and the average annual precipitation is 11 cm.

Sellmann et al. (1972) stated that approximately 64 percent of the area had prominent polygonal ground relief. The polygonal ground caused by ice-wedge formation is seldom higher than 1.0 m, and 1.5 m is the upper limit. Otherwise, the terrain is typically low, with small but abrupt (< 2 m) relief features.

The vegetation generally consists of a mat of moss, lichens, grasses, sedges, and dwarf willows, usually not more than 20 to 30 cm high. The landscape includes wet tundra, ponds, lakes, and meandering streams.

Brown et al. (1968) calculated that approximately 21 percent of the land north of 71° was covered with lakes. The basins are fairly

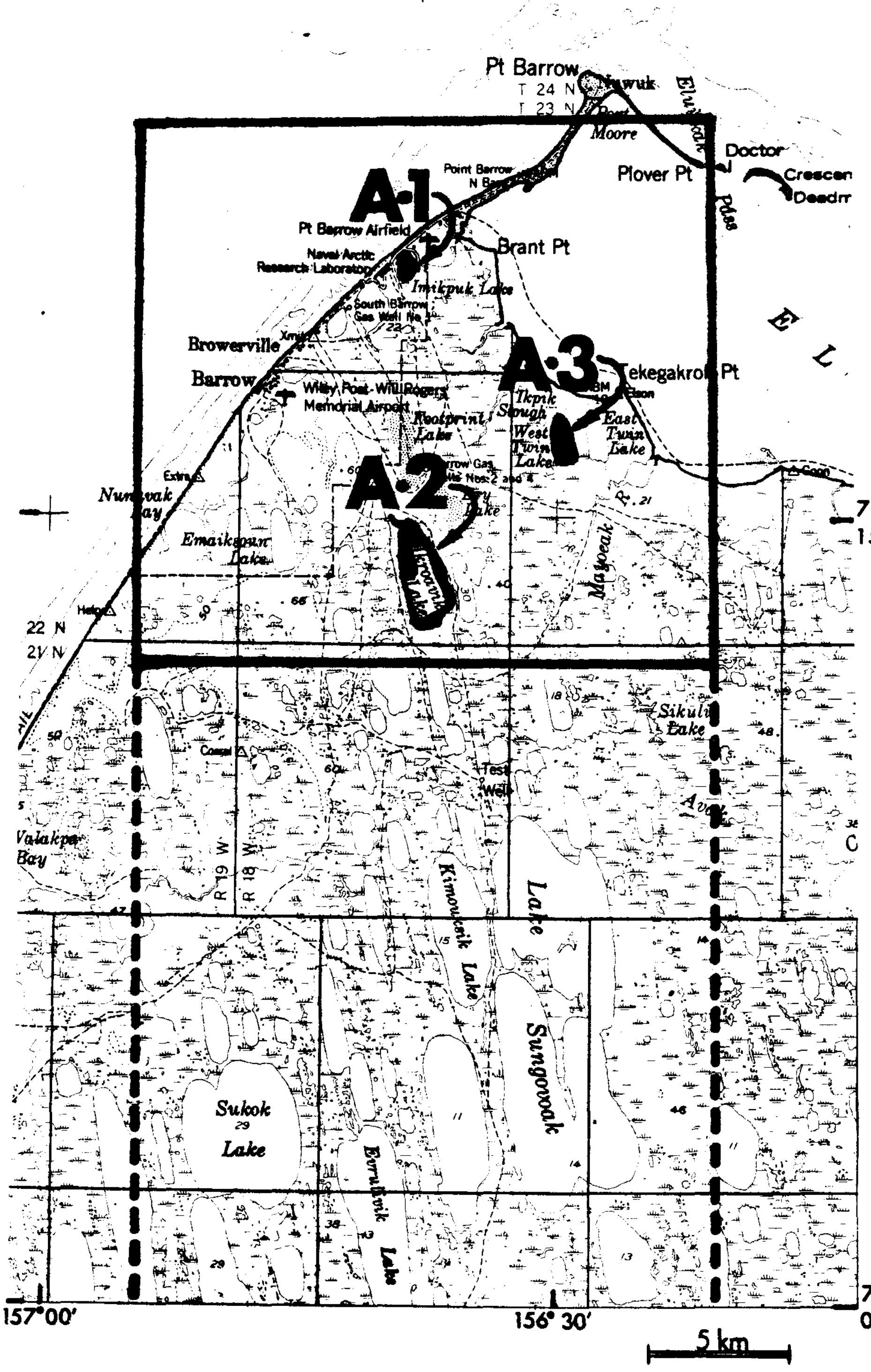


Fig. 11. Study Area A — Northern Coastal Plain lakes A-1, A-2, and A-3.

uniform in the middle and may have smooth transitional or abrupt shores. Large lakes have their major axes oriented approximately 10° west of true north as do the 3 study lakes A-1, 2, and 3.

Study Area B - Mid-Coastal Plain

The Study Area B lakes are approximately 100 km due south of the "A" lakes, and the climate there is considerably more continental in nature. The "B" lakes receive less fog and wind and higher air temperature as a result of their distance from the Arctic Ocean.

Study Area B is on the southern portion of the coastal plain within an area of dense lake concentration (Figure 12). The number of lakes and percentage of surface covered with large lakes is greater than within Area "A". The lakes are north/south oriented but less dramatically than in Area "A". Many of the "B" lakes are shallow (2 to 3 m) as in "A", but there also exist many lake basins from 3 to 12 m deep. The deep lakes most often have an elongated north/south oriented deep basin axis. Extensive sandy shoals on the eastern and western shores make the lake surfaces less elongate and more oval in shape. The sandy shelves drop off sharply at from 0.5 to 1 m depth changing to soft bottom sediments and detritus after the shelf break.

Study Area C - Foothills

Study Area C is in the Foothill Province, where lakes are much less numerous than on the coastal plain. The map of the Foothill Lakes Study

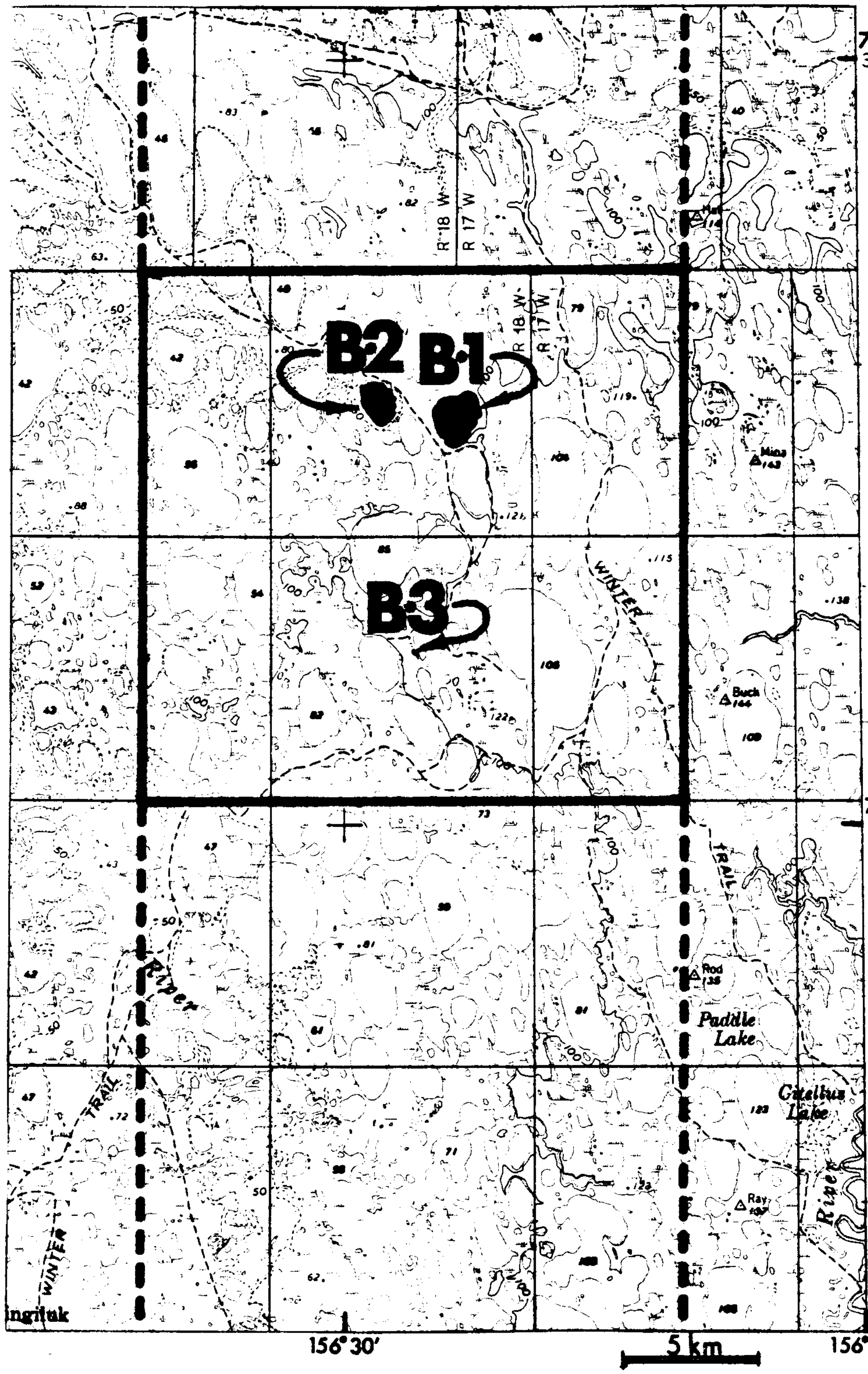


Fig. 12. Study Area B — Mid-Coastal Plain lakes B-1, B-2, and B-3.

Area (Figure 13) shows few lakes, some palustrine habitat, and an abundance of dry land. The Smith Mountain Lakes, including Lake C-3, are at about 335 m elevation, while C-1 and C-2 are at about 457 m. The maximum elevation within the area illustrated is just under 906 m. The north/south axis orientation of lakes is not evident in this area. Each lake has different basin morphology, resulting primarily from the geomorphology of the local terrain, rather than similar morphology caused by thaw features. Although this area receives more precipitation than the other 2 areas, the water drains from the area because of the greater terrain relief.

Study Area C has a more continental climate than do study areas A or B. Summer air temperatures of 15°C are not uncommon, because the area gets less frequent fog cover and wind than do more northern areas. The "C" lakes are 300 km south of the "A" lakes and 200 km south of the "B" lakes.

The areas and lakes selected reflect the diversity of lake basin morphology and climatic gradient encountered across the Alaskan arctic.

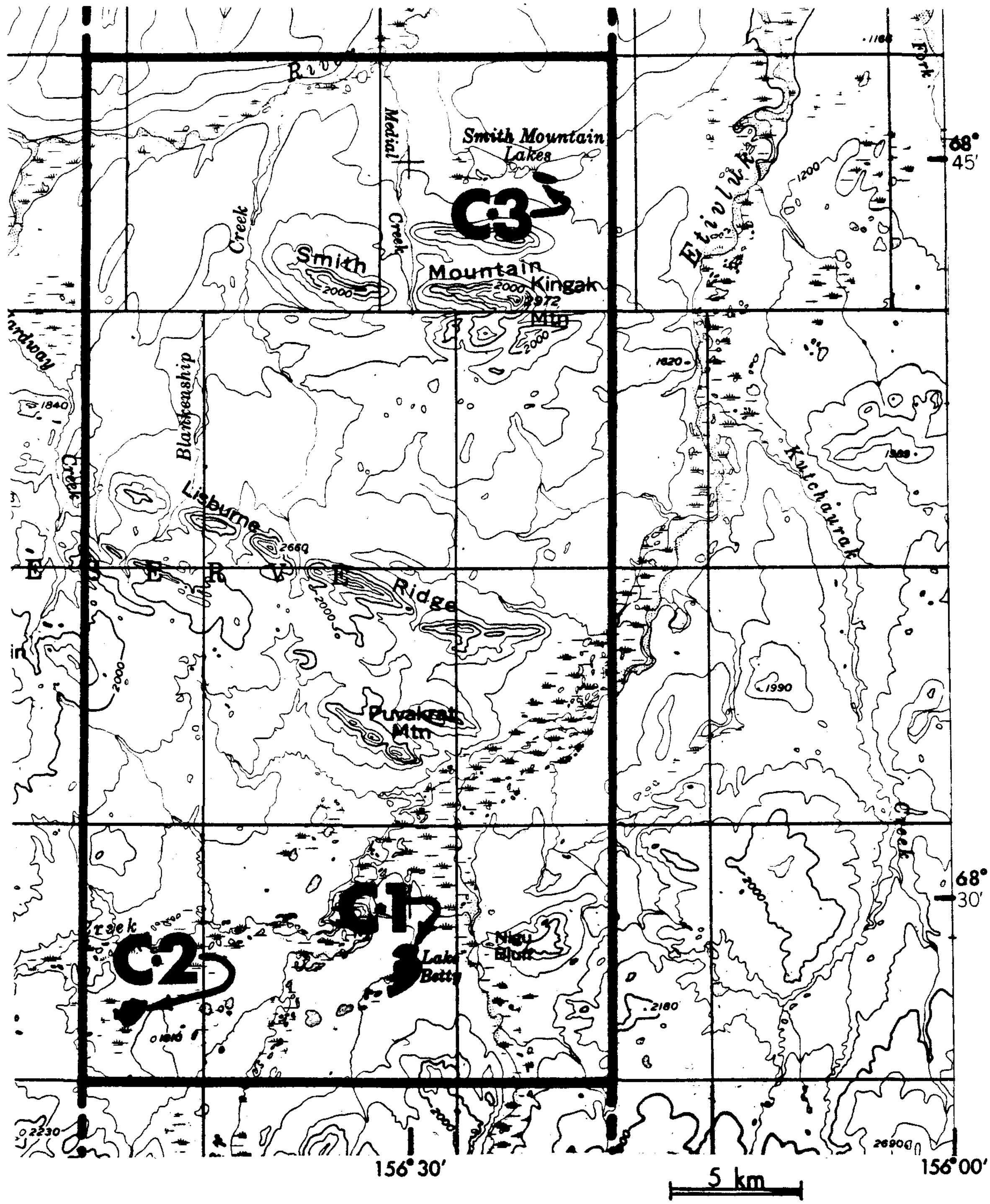


Fig. 13. Study Area C — Foothill lakes C-1, C-2, and C-3.

CHAPTER II

A METHOD FOR DETERMINING LAKE ISOBATHS USING ICE THICKNESS AND SIDE-LOOKING AIRBORNE RADAR DATA

INTRODUCTION

Side-Looking Airborne Radar (SLAR) Detection of Winter Water

Bathymetry acquired from study lakes is used to verify the hypothesis and application, that regional winter SLAR images and ice thickness can be used to determine arctic lake isobaths. The 9 study lakes were sampled for ice thickness coincident with sequential SLAR imaging of the study transect (Figure 1) during ice growth and decay through the winter and spring 1978-79. The fathometer transects discussed in Chapter III provided adequate bathymetry (Figures 2 to 10) for the study lakes. SLAR imagery and ice thickness data were acquired to compile sufficient empirical data to verify a hypothesis first developed by Sellmann et al. (1975a) and to investigate a technique utilizing these data to provide lake depth contour information. From studying winter SLAR imagery over arctic lakes, Sellmann et al. concluded that freshwater lakes with weak SLAR returns were frozen to the bottom, while lakes with strong returns were not. Weak SLAR signals were returned from saltwater bodies covered with a smooth (i.e. without pressure ridging or ice rafting) ice sheet whether they were frozen to the bottom or not. Sellmann et al. had little lake depth data with which to analyze the SLAR imagery; however, the fact that most thaw lakes are at or near freezing depth provided a lake depth index for general interpretation. Elachi et al. (1976), Weeks et al. (1977, 1978), and Arcone et al. (1979) provided further investigation and reporting of the unique SLAR signal returns from arctic lakes. SLAR and lake data have continued to be limited in spatial and temporal extent, but all evidence, including this investigation, has substantiated the original hypothesis that strong SLAR signal returns come from shallow, arctic, freshwater lakes not frozen to the bottom. Data from the study lakes have also provided insight into the mechanisms that create various SLAR signal returns received from these lakes and into additional depth information incorporated in subtle differences in SLAR signal returns.

The Need for Detection of Winter Water

A dearth of lake depth information exists for all but a few among thousands of Alaska arctic lakes. Although tens-of-thousands of water bodies exist, winter water supplies are limited in the vast arctic area because most of the water contained in these shallow basins is frozen during midwinter. Numerous researchers have summarized the present state of water depth inventory and professed the need for more (Greenwood and Murphy 1972, Furniss and Ward 1975, Alaska Water Quality Management Program 1977, Wilson et al, 1977, and U.S. Geological Survey 1979). Recent field surveys have not increased the inventory data base significantly (NANA Env. Sys. Inc. 1976a and b, McFadden 1978, National Pet. Res. in Alaska Task Force 1978, Mellor et al. 1978, Reynolds et al. 1979).

Water depth can be an important parameter for describing these lakes. Lake volumes can be estimated from water depth contours. Use of lakes for surface transportation and prediction of fish resources can also be estimated from depth contours. A water resources panel reporting on significant results obtained from Earth Resources Technology Satellite-1 noted that the volume of water in lakes is more important than area, and that research needs to be devoted to finding remote-sensing applications for estimating water volumes (Salomonson and Rango 1973). Classical methods of summer water depth inventory by lead line and fathometer depth profiles or winter site depth measurement by ice auger will always be used for site-specific determinations but are inadequate for regional inventory. The number of lakes, size of the area, harsh environment, cost, and speed with which lake depths may change dictate the need for a method of inexpensive, periodic, rapid, and regional inventory of water depths in arctic lakes. Regional water depth data would permit more practical development and management of arctic aquatic resources than are done now.

Alternative Methods for Detection of Winter Water

Alternative methods for determining water depths are discussed prior to describing the SLAR method investigated. Physical measurements may be acquired at single sampling points, along a line (profile), and in 2-dimensions that form an image. Instruments available today can provide water depth information in each of the above dimensions; however, the trend is for less reliable or refined depth measure with increasing dimensionality. Increasing dimensionality and greater regional coverage are often accompanied by a decrease in measurement scale and resolution. For example, the most accurate water depth may be measured at a single point with a lead line at a scale of 1 cm of line to 1 cm of water. A recording fathometer may reduce the scale to 1 cm of record to 1 m of water, providing less precise depth measurements but an increase in information (i.e. profile). Qualitative inference may be necessary to derive water depth information from a 2-dimensional image, providing even less depth resolution. This severely reduces measurement accuracy. Measurement accuracy is sacrificed to obtain a regional method for determining water depth information at reasonable cost.

Imaging methods presently provide the only feasible way to collect regional information. Single-point and profiling methods require visits to individual lakes. This cannot be considered a cost-effective regional approach; however, these methods may be desirable for detailed study of a lake. Methods that require lake surface encounter or aerial passes over a specific lake and have little regional application are discussed first.

Fathometer and lead-line depths were used to define lake bathymetry for the 9 study lakes. Another method requiring summer lake visits was described by McFadden (1965) for determining mean lake depth using seiche period measurements. These methods require surface visits to each lake during months when they are free of ice.

Kim et al. (1975) and Hoge et al. (1980) reported on the development of an airborne green light laser bathymeter. Laser profiling for mapping water depths has been cnly moderately field tested and is not presently available for operational use. The equipment is heavy, sophisticated, and sensitive to vibration and small changes in water turbidity. Laser bathymetry must be accomplished during the summer ice-free period when cloud and fog cover would limit laser missions. Although laser scanning systems capable of 2-dimensional mapping are presently under construction (Hoge, pers. comm.), no laser water depth imaging systems exist to date.

Airborne and satellite systems also have some capability to determine summer lake depths. Changes in water depth are visible across lake basins in the summer and can be recorded in aerial photography and satellite multispectral scanner data. Water depth, suspended solids, and lake bottom materials produce these differences in reflected light intensity. Lyzenga (1978) proposed a method for extracting water depth measurements and bottom material type from multispectral scanner data. Qualitative depth inferences can be made from single aerial photographs, and the potential should exist to plot depth contours of shallow water (< 4 m) with stereopair analysis. Photographic analysis (or use of any image produced by visible spectral energy) is limited, however, because it requires extremely clear lake waters, knowledge of bottom substrate and clear weather conditions. In addition, presently available photographic films lack sufficient water penetration. The methods discussed thus far require open water with no ice cover. The lakes are free from ice cover for approximately 2 to 3 summer months during which time fog and clouds obstruct photographic and satellite sensor views most of the time.

Arcone et al. (1979) reported on low frequency (< 1 MHz) resistivity methods for locating water beneath ice and frozen soils. They listed both surface and airborne systems that measured ground resistivities using surface impedance (radiowave) and magnetic induction techniques. Unfrozen areas below ice covered lakes and streams could be identified with resistivity profiles that may reveal good winter ground water sources in permafrost regions. The last of the profiling systems is the impulse radar. Impulse radar profiling has been tested both from the ice surface (Campbell and Orange 1974, Vickers et al. 1974, Outcalt 1979) and more recently airborne from a helicopter (Kovacs 1978, Kovacs and Morey 1979). The impulse radar technique is capable of profiling ice thickness and, with proper conditions, the lake bottom as well. It can be used to determine where the lake ice is frozen to the bottom and where free water exists beneath the ice cover.

The remaining systems to be discussed are airborne or satellite systems that provide images with sufficient 2-dimensional coverage for regional application. The first of these involves the use of aerial photographic or satellite coverage during melt and break-up of Alaskan arctic lakes. As described in Chapter III - Temperatures results, the shallowest (< 1 m) of lakes and ponds melt first. They absorb solar energy and appear dark in photographs and satellite imagery. Lakes and ponds in the mid-depth category (1 to 2 m) are frozen to the bottom and collect melt water on the surface of bottom-fast ice. This creates a light blue or green color to the observer and medium intensity solar reflections recorded in photographs and satellite images. Lake areas deeper than the maximum winter freeze ($\gtrsim$ 2 m) have floating ice covers. Melt water drains off the surface, thus sustaining a high albedo. The high albedo retards melting and provides high intensity solar reflections or white photographs and satellite images in the areas retaining floating ice covers. Shallow shelf areas in deeper basins are defined by dark moats which surround the white floating ice cover over the deep basin. This phenomenon is best recorded during the middle of June but varies from year to year and with climatic gradient across the arctic in any given year. Lakes melt more rapidly in the foothills of the Brooks Range and are in a different successional stage of melt than the northern coastal lakes throughout break-up. Many other investigators have noted this phenomenon (Brewer 1958), and some have attempted and are still attempting to classify lakes by depth using satellite data (Sellman et al. 1975a, Wilson et al. 1977, Hall 1977). This qualitative technique is reliable when cloud-free synoptic scenes can be acquired within the few days that the lakes are at the correct stage of melt, and if the geographic variations in climate and melt are taken into consideration and documented with sufficient lake verification data.

McFadden (1965) used freezing dates to estimate mean lake depths. Since deeper lakes react more slowly to changes in climate than shallow ones, it is feasible to estimate mean depths by comparing freeze dates with proper lake verification data. McFadden was able to get a good correlation between mean depths obtained by fathometer soundings and estimates by seiche measurements and lake freeze over dates in central Canadian lakes. He also noted that freeze over coincided with seasonal change to winter much more closely than break-up coincided with the seasonal change to summer. This is the result of the enormous amount of energy required to return the thick layer of ice, grown throughout the winter, to the liquid state. Break-up, with its longer period of ice/water phase change, provides a better index for classifying ranges in lake depth than does freeze over, but again these are very qualitative.

Passive microwave and infrared imaging systems have limited capability for identifying free water beneath ice cover. The Electrically Scanned Microwave Radiometers (ESMR) on both the NASA Convair 990 and on Nimbus Satellites have poor resolution ($\sim$ 500 m and 30 km, respectively) restricting analysis of Alaskan arctic lakes. Hall (1977) found that ESMR brightness temperatures increased with increasing ice thickness on all lakes studied. ESMR imagery has the benefit of being relatively unaffected by cloud cover unless liquid water is present. Thermal infrared scanning systems are also capable of detecting changes in temperatures radiating from lake surfaces. Airborne infrared imagery can be acquired at good resolution (a few meters) but is affected by cloud cover. Both infrared and ESMR imagery can be extremely complex to analyze for changes in emitted radiation. Variations in ice and snow cover thickness and density affect their insulating quality and, in combination with the various thermal characteristics of the underlying water or substrate, add complexity to emitted radiation.

Arcone et al. (1979) recently produced a good summary of remote-sensing systems capable of detecting arctic water supplies. Weisnet (1974), Page and Ramseier (1975), Campbell et al. (1975), and Hall and Bryan (1977) reported on most of the remote-sensing techniques presently being investigated for measuring snow, ice, and water. Of all the systems reviewed, the combined capability and cost effective regional data acquisition of scanning radar systems make these prime systems for aquatic resource investigation on Alaskan arctic lakes. The SLAR system used for this study could provide film image products only. Scanning radars, such as satellite and airborne Synthetic Aperture Radar (SAR) systems, can provide digitally recorded data that are conducive to computer aided geometric correction and data analyses. Digital data recording should be considered for a future operational mapping system but was not available and was not necessary for this feasibility study.

Description of SLAR and Its Assets

The SLAR system used actively transmits its own energy at a wavelength of approximately 3 cm ($\approx$ 9.2 GHz frequency) (U.S. Dept. of Army, 1979). This energy can be transmitted through fog and clouds during the day or night with no degradation of the image. The Arctic Coastal Plain is seldom without fog or clouds throughout the year, and daylight is brief or nonexistent during winter months. SLAR provides a 24 hour year-round capability that other passive systems relying on visible spectral energy (i.e. aerial photographs and Landsat MSS) do not.

The SLAR energy is also capable of penetrating snow and ice cover so that the resulting image depicts terrain, lakes, and cultural features that are comparable with existing charts for visual geographic location of sites or lakes of interest. Figure 14 is a section of study transect SLAR image taken over the Study Area "A" lakes on 21 February 1979.

Sections of SLAR imagery acquired over the study transect were excerpted (Figures 14, 15 and 16) from a 21 February 1979 mission to illustrate typical winter imagery over the lake study areas A, B, and C, respectively. All areas were completely covered with snow and ice. Landsat and aerial photographs would depict the areas as barren white landscapes similar to a white sand desert with little to no terrain relief. Ice thicknesses were approximately 1.4 m at the northern end of the study transect and 1.2 m at the southern end.

Figure 14 should be compared with the chart of Area "A" in Figure 11. Both figures are at their original scale of 1:250,000. Although some of the lakes in Figure 14 are white and others are black, the shapes and sizes of lakes can be discriminated from the surrounding tundra. The lake boundaries in Figure 11 are helpful for initial discrimination, but once the visual criteria are established most lakes are identifiable in SLAR imagery without the aid of charts. Lakes A-1, A-2, and A-3 are gray, white, and black, respectively. Lake A-3 had an aircraft landing strip and parking apron bulldozed on its

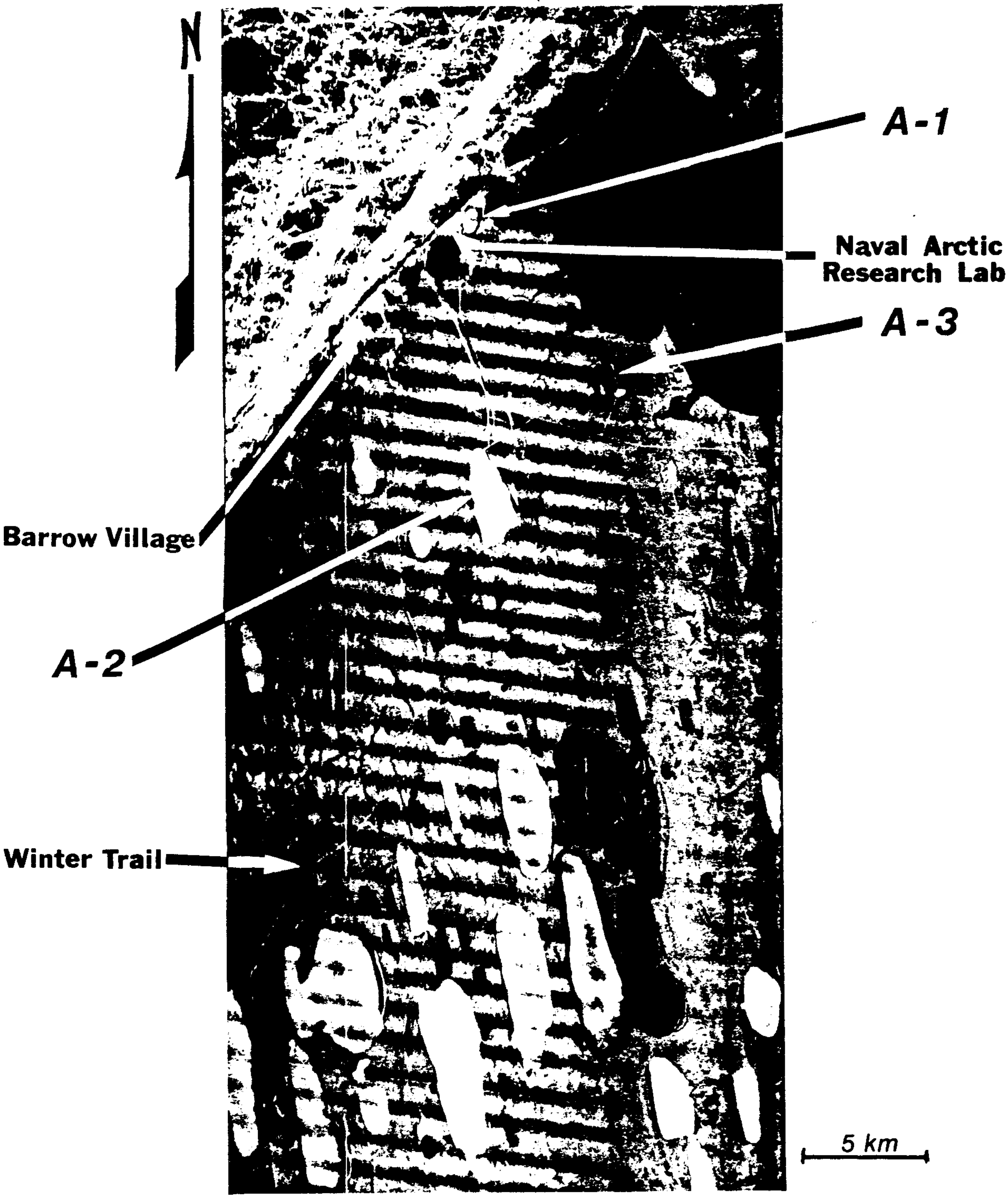


Fig. 14. SLAR image acquired over Northern Coastal Plain lakes A-1, A-2, and A-3, 21 February 1979.

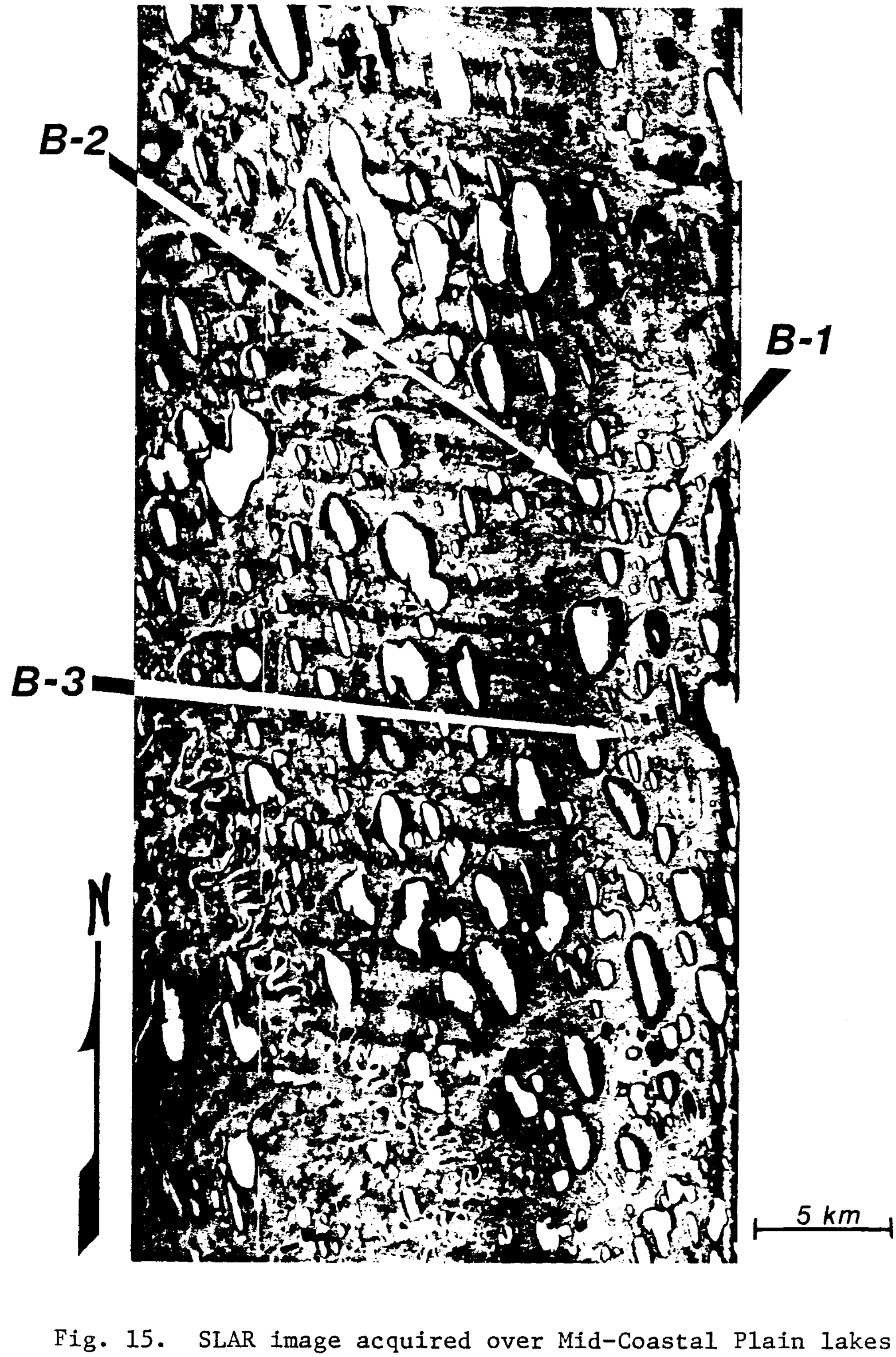


Fig. 15. SLAR image acquired over Mid-Coastal Plain lakes B-1, B-2, and B-3, 21 February 1979.

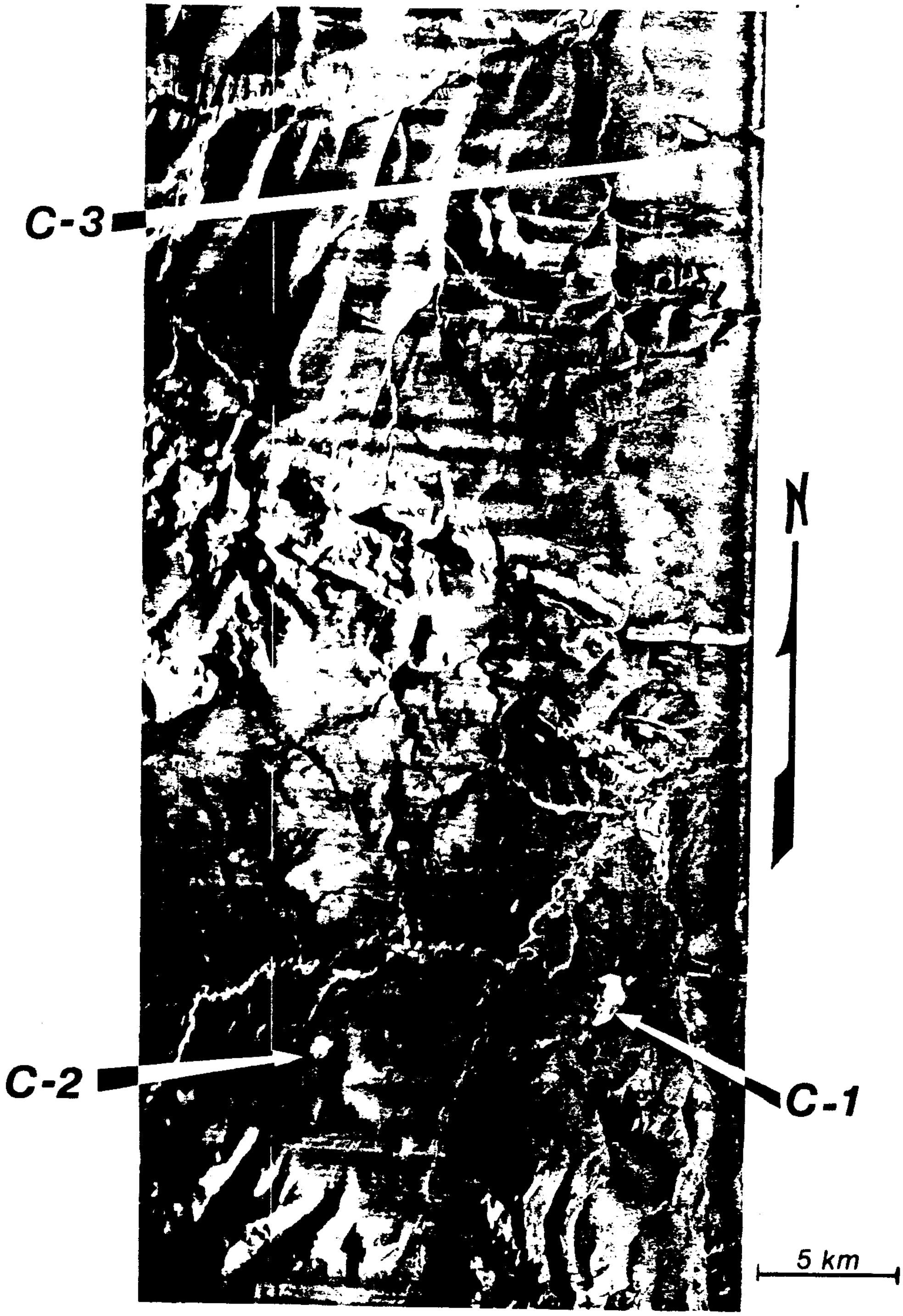


Fig. 16. SLAR image acquired over Foothill lakes C-1, C-2, and C-3, 21 February 1979.

surface. These are visible in the image. The Naval Arctic Research Laboratory (NARL) complex and Barrow Village are depicted as white blocks along the Arctic Ocean shore. The many thin white lines projecting south from the NARL/Barrow area are trails and roads across the tundra. The brightest line north of Lake A-2 is a gravel road that was under construction to the gas wells within the network of trails just above A-2. The very thin line identified as a winter trail in Figure 14 is part of a compacted snow trail used between Barrow and Atkasook Village, 90 km south of Barrow. SLAR applications for recording and monitoring winter trails became a spin-off of this study (Mellor 1980).

A SLAR image of the Mid-Coastal Plain "B" lake area for the same 21 February 1979 date is shown in Figure 15. Study lakes B-1 and B-2 and Pond B-3 are labeled. Map orientation for this SLAR imagery may be obtained from Figure 12. The lakes in Figure 15 are more numerous, smaller, and have white centers more frequently than those in Figure 14. Lakes B-1 and B-2 have black perimeters where the ice cover is frozen solidly to the lake bottom on wide shallow shelves. Lake B-1 has 2 subtle ovals with darker gray tones within the white center. These darker areas correspond closely with the eastern and western basin deeps defined by Lake B-1 bathymetry in Figure 5.

Finally, SLAR imagery of the Foothill "C" lake area is shown in Figure 16. The area outlined in Figure 13 is about the same as that depicted in the Figure 16 SLAR image. The southern half of the Lake C-1 SLAR image is darker than the northern half. The darker portion of the image again is coexistent with the deeper portion of the basin.

Lake C-2 does not have a clearly defined shoreline in this image. This is probably because the hill just east of the lake partially blocked the SLAR signal during the mission. A major advantage in using SLAR for lake studies in the Alaskan arctic is the flat terrain of the Arctic Coastal Plain. The aircraft can be flown at lower than normal altitudes, and receive strong signal returns from lakes without interference, such as feature distortion or shadows from terrain features with high relief. Lake C-3 is entirely black and frozen to the bottom in this 21 February image; however, other portions of the Smith Mountain Lakes to the east and west are still white, having not yet frozen to the bottom.

Specific variations in SLAR signal reflections are related to environmental conditions and causes learned from lake verification data later in this Chapter and then are used in retrospect to predict lake constituent differences in Chapter IV. The study objectives here were to develop a method useful for determining water depth contours within Alaskan arctic lakes and to learn more about the unique SLAR signal returns from these lakes. With this information water volumes could be calculated, water balance could be studied, and aquatic constituents might be better utilized and managed.

METHODS

Past SLAR investigations of arctic lakes have used a single SLAR image over a number of lakes about which little information was available. If ground verification information was obtained for comparison with the imagery, it was usually limited and not acquired at the same time as the imagery. Costly logistics and extreme environmental conditions dissuade investigators from remote arctic field investigations during the dark and cold of winter. This investigation was designed to obtain multitemporal SLAR imagery over the study transect (Figure 1) within which are 9 study lakes that have been studied extensively throughout 2 summers. Three additional lakes, 30 km north of the "B" lakes, were also selected for SLAR verification studies. Winter lake verification data were acquired within a few days of SLAR image missions.

The dates during which SLAR imagery was acquired for this project are listed below;

1978 - 5 December

1979 - 21 February, 20 and 21 March, 3 and 12 April, 15 May, 5 June, and 14 August

1980 - 7 thru 14 April

The north/south study transect was imaged as a transect on every date except the last. During 7 to 11 April 1980, east/west transects were flown that imaged the study transect as part of many flight lines. The April 1980 mission will be discussed in more detail in Chapter IV applications. Figure 17 shows all the SLAR imagery flight lines flown during the winter 1978-79. All flight lines shown with the exception of the study transect were imaged only once and were completed during 3 to 12 April 1979. The study transect was imaged at least once during 7 different months of the year. Ice covered the surface of the lakes during

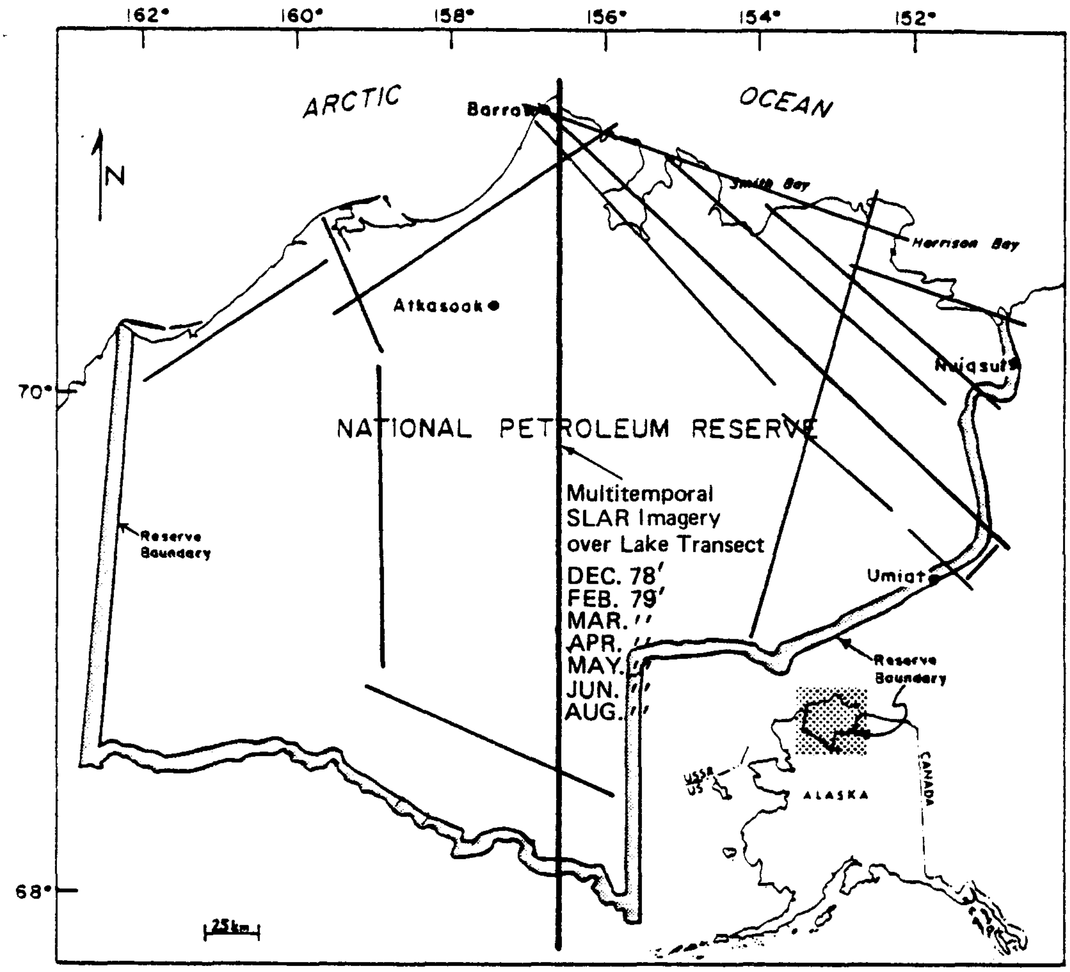


Fig. 17. SLAR image flight lines, December 1978 through August 1979. The center, vertical study transect flight line, was imaged during 7 months, while all other flight lines were imaged only once, in April 1979.

6 of these 7 months; however, 1 summer mission was flown on 14 August 1979, during which all lakes were ice-free.

SLAR imagery was acquired with an AN/APS-94E radar surveillance set (U.S. Dept. of Army 1979) mounted on an OV-1D Mohawk aircraft (U.S. Dept. of Army 1978). The radar was X-band operating at a transmitter frequency variable from 9.1 to 9.4 GHz ($\approx$ 3 cm wavelength). The system was quoted to have a resolution of 30 m or 30 lines/mm·min. It could be operated at 1 of 3 ranges (width of terrain imaged) 25, 50, and 100 km at scales of 1:250,000, 1:500,000, and 1:1,000,000, respectively. The Mohawk aircraft is a 2 place twin turboprop that cruises at approximately 250 kts. The aircraft was operated by U.S. Army personnel out of Fort Wainwright in Fairbanks, Alaska.

SLAR imagery was acquired by scanning with a pulsed radar signal out of one side of the aircraft (Figure 18) at an oblique angle such that it never images directly below the aircraft. The radar signal, transmitted along a scan perpendicular to the path of the aircraft, strikes the earth's surface and is reflected away from the aircraft, absorbed by the medium it encounters, or reflected back toward the receiving antenna on the aircraft. The returning signal is processed, and amplitudes are recorded as analog brightness (gray scale) on a continuous strip of black and white photographic film. This film is developed on board the aircraft during flight and is available for almost real-time analysis in the air. The imagery, as a negative film transparency, was removed from the aircraft upon landing to aid in collection of ground verification data. When the film was returned to

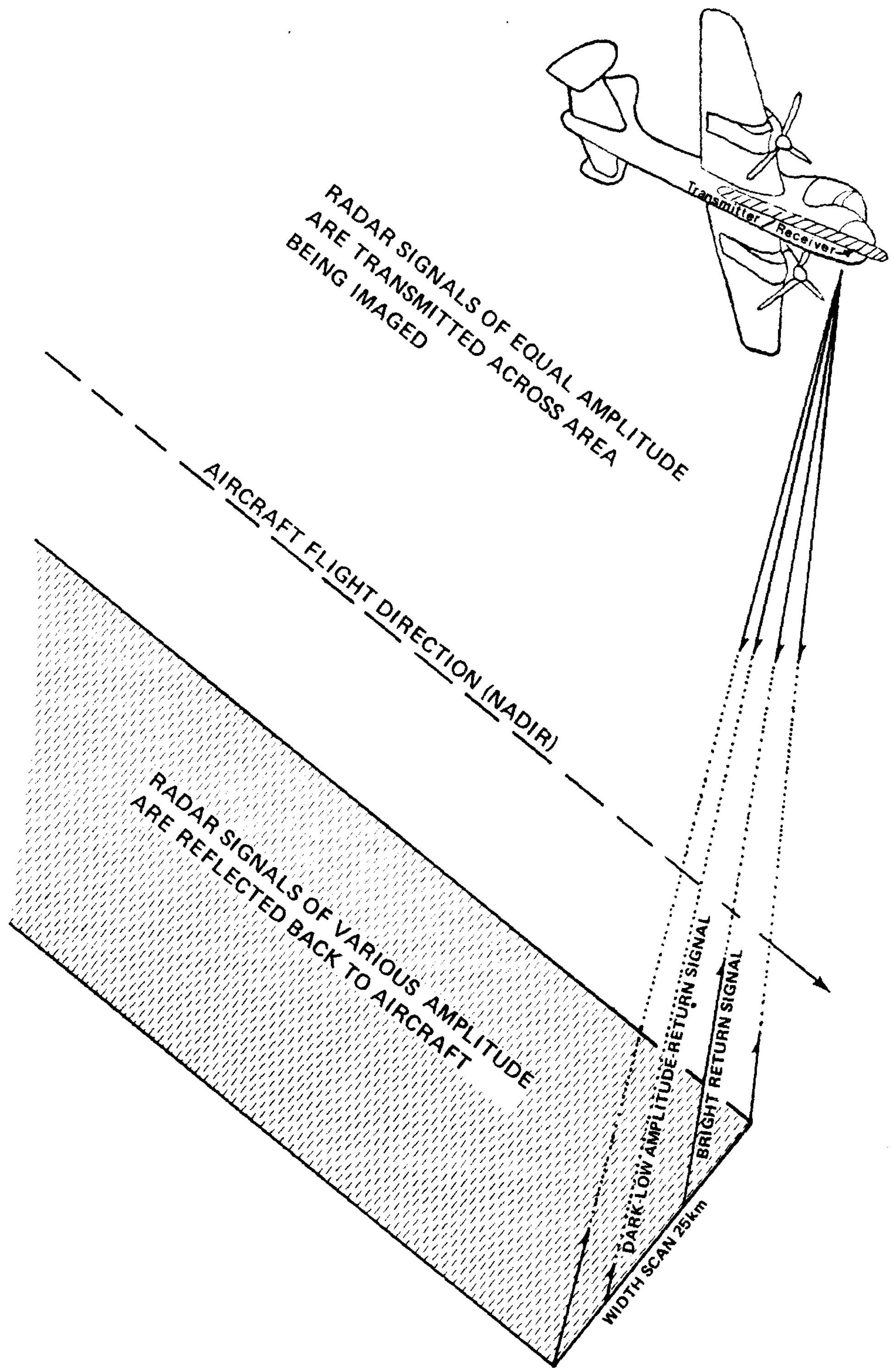


Fig. 18. Conceptual diagram of side-scanning radar obtaining a continuous strip SLAR image.

Fairbanks from the field, a positive contact print was produced from the negative and used for further study. The negatives are archived at BLM offices in Fairbanks, Alaska.

Areas from which a strong return signal is received are white on the positive print, while areas with a weak or nonexistent radar signal return are dark. The strip of imagery is approximately 10 cm wide, covering a 25 km swath at 1:250,000 scale. The 1:250,000 scale imagery has advantages over the 2 smaller scales. Imagery quality is increased because of reduced angles of signal incidence on the earth's surface and from the increased size of lakes at the larger scale. The 1:250,000 scale provided the best possible resolution for this SLAR system and is also convenient for comparison by overlay upon 1:250,000 U.S. Geological Survey quadrangle maps. This scale is large enough for regional coverage and provides maximum lake detail. A variety of flight altitudes at 3,000 ft (915 m), 5,000 ft (1,524 m), and 10,000 ft (3,049 m) above ground level and range delays (distance of image swath from aircraft) were used in an attempt to achieve maximum returning radar signal strengths. A single attempt to image lakes at 1:500,000 scale was only moderately successful. The increased regional coverage (50 km swath) did not make up for the reduced lake size (scale) and loss of definition in the imagery. After a few tests in 1978 and early 1979, imagery was acquired at 1:250,000 scale with no range delay from 5,000 ft (1,524 m) above ground level. The lack of range delay provided a swath imaged as near to the nadir of the aircraft as the system was capable of providing, thus reducing the angle of signal incidence at the lake/ground surface.

Ground verification data were collected for 2 purposes. The first was to obtain enough empirical data to ensure that dark areas within lake basins on SLAR imagery were frozen to the bottom and that the bright areas had a layer of unfrozen water beneath the ice cover. The second purpose was to observe conditions that might explain the mechanisms surrounding the unique SLAR images acquired from arctic lakes.

Lake bathymetry maps were assembled from summer fathometer profiles to provide baseline water depths in 12 lakes within the study transect. Summer vertical aerial photographs were used to aid in the production of lake bathymetric maps. They aided in shoreline definition and placement of some depth contours where abrupt changes in lake depth were visible in the aerial photographs. A Bausch and Lomb Stereo Zoom Transfer Scope was used for overlay and comparison of map, photograph, and SLAR imagery shorelines and water depth interfaces of interest.

RESULTS AND DISCUSSION

SLAR Lake Image Interpretation

In an effort to reduce the amount of SLAR imagery reproduced to illustrate the technique to be described here, a small area within the transect between areas "A" and "B" is used. This area (Figure 19) is about 75 km south of Barrow and 30 km north of Study Area B. It contains 3 large lakes in close proximity that have been numbered SLAR-1, SLAR-2, and SLAR-3. These lakes have subtle differences in basin morphology which will help illustrate and verify SLAR imagery interpretation.

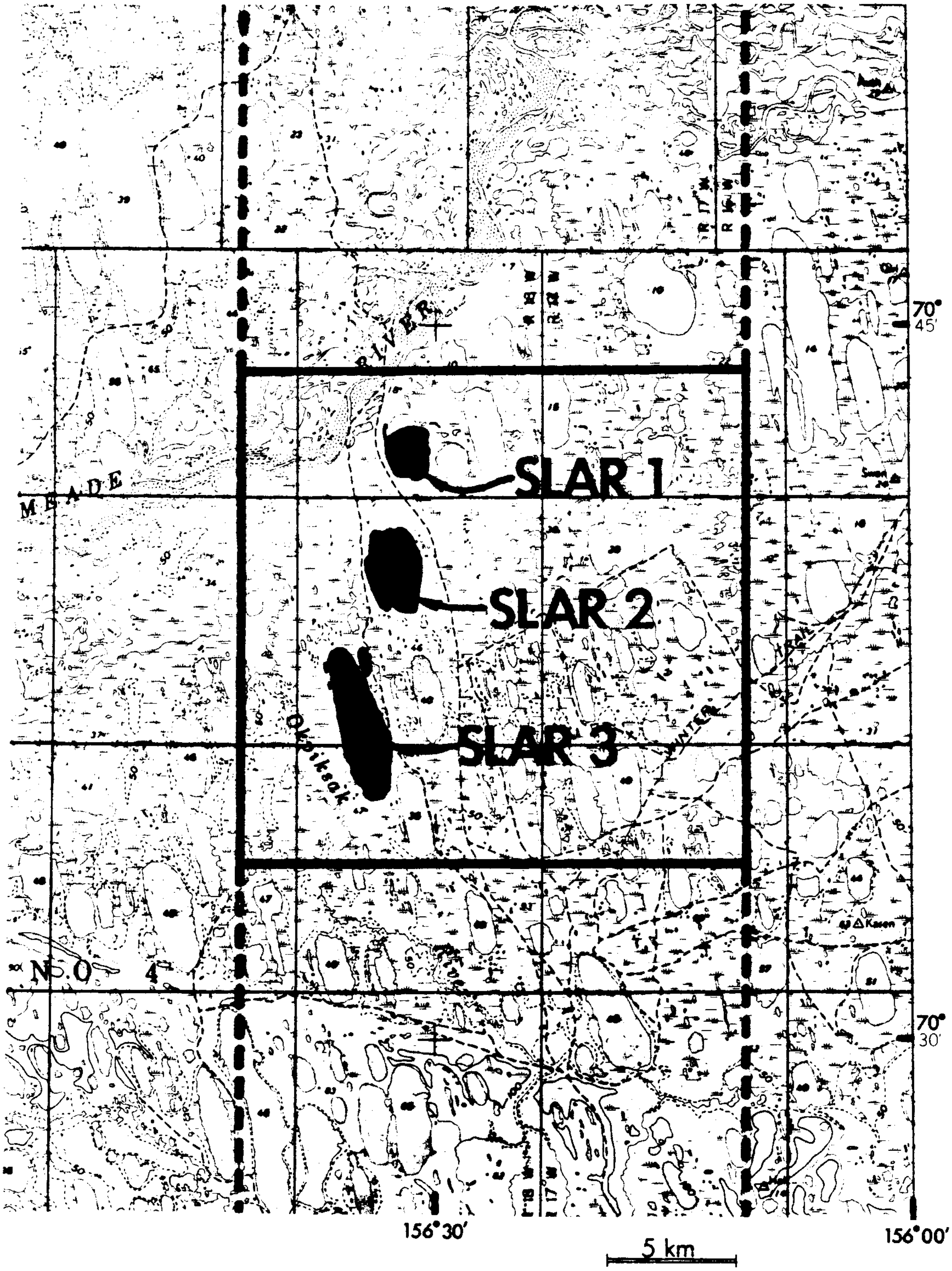


Fig. 19. Study area containing SLAR verification lakes SLAR-1, SLAR-2, and SLAR-3.

Basin Depths Within the Range of Ice Cover Thicknesses

SLAR-1, 2, and 3 verification lakes are thaw lakes not exceeding 2.2 m maximum depth. The bathymetry for the 3 lakes was acquired on 1 September 1979 by making 2 fathometer transects on each lake as illustrated in Figures 20, 21, and 22. The depth profiling methods are described in Chapter III. Depths are illustrated with 0.5 m contours estimated from the fathometer transects with contour placement assisted by aerial photographic interpretation. Summer specific conductance ranged from 123 μmhos to 300 μmhos (SLAR-3 and SLAR-2, respectively).

Lake SLAR-1 was the deepest (2.2 m) and had little to no shelf area (Figure 20). The 1.5 m depth contour was less than 100 m from shore around the entire basin, which was 296 ha in area.

Lake SLAR-2 had a maximum depth of 1.8 m and an area of 600 ha (Figure 21). Most of the basin was from 1 to 1.5 m deep. A 0.5 m shelf area up to 350 m wide was on the eastern shore.

Lake SLAR-3 had a maximum depth of 1.9 m and had the largest area (848 ha) of the 3 SLAR lakes (Figure 22). Water depths increased slowly to the 1.5 m contour, up to 600 m from the eastern shore, and up to 200 m from the western shore. No fathometer data were acquired within the bay on the northeastern end of SLAR-3.

SLAR imagery acquired over the 3 SLAR verification lakes on 21 February 1979 is shown in Figure 23. This image is at the same scale (1:250,000) as the map of this area in Figure 19. The ice thickness on 21 February 1979 at 70°37'N latitude in the vicinity of these lakes was approximately 1.4 m. A comparison of the 1.5 m depth contours for

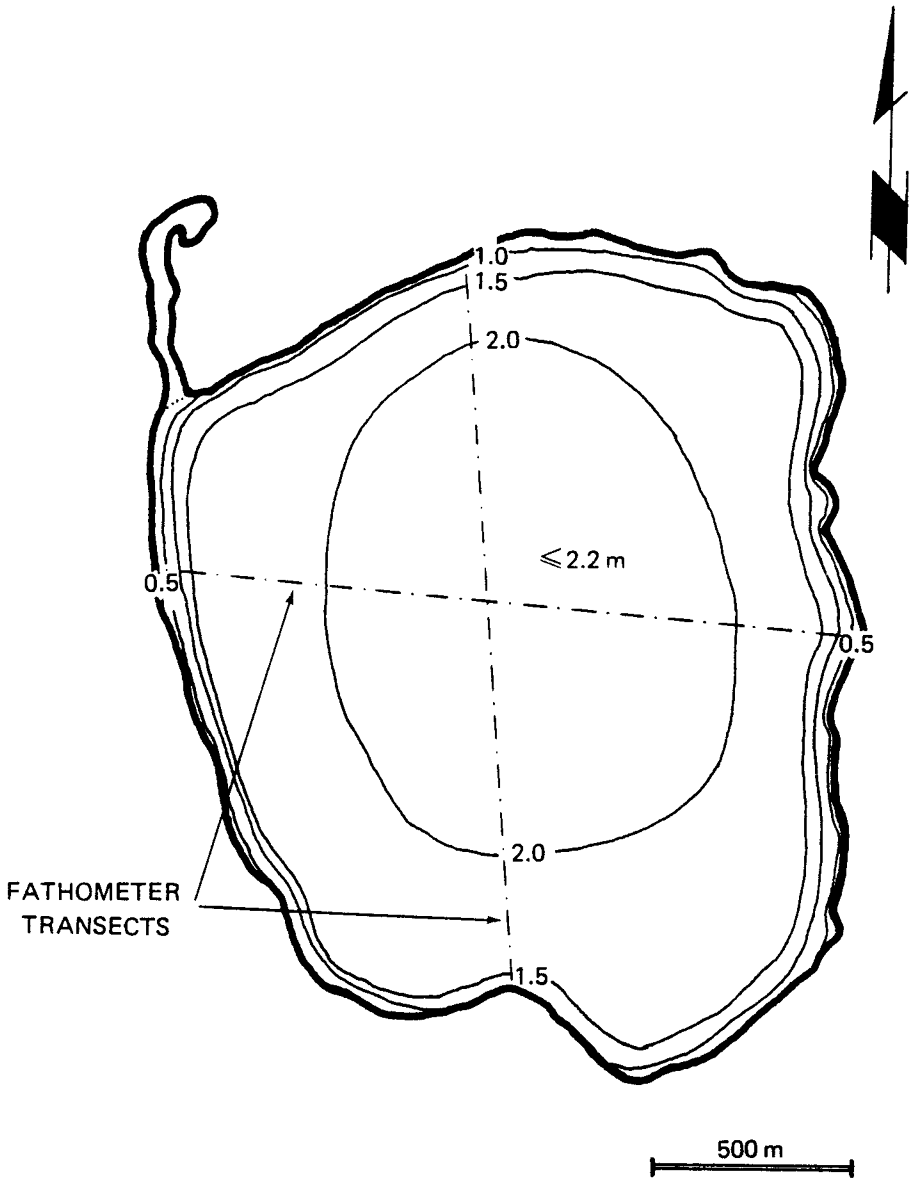


Fig. 20. Depth contours (m) in Lake SLAR-1.

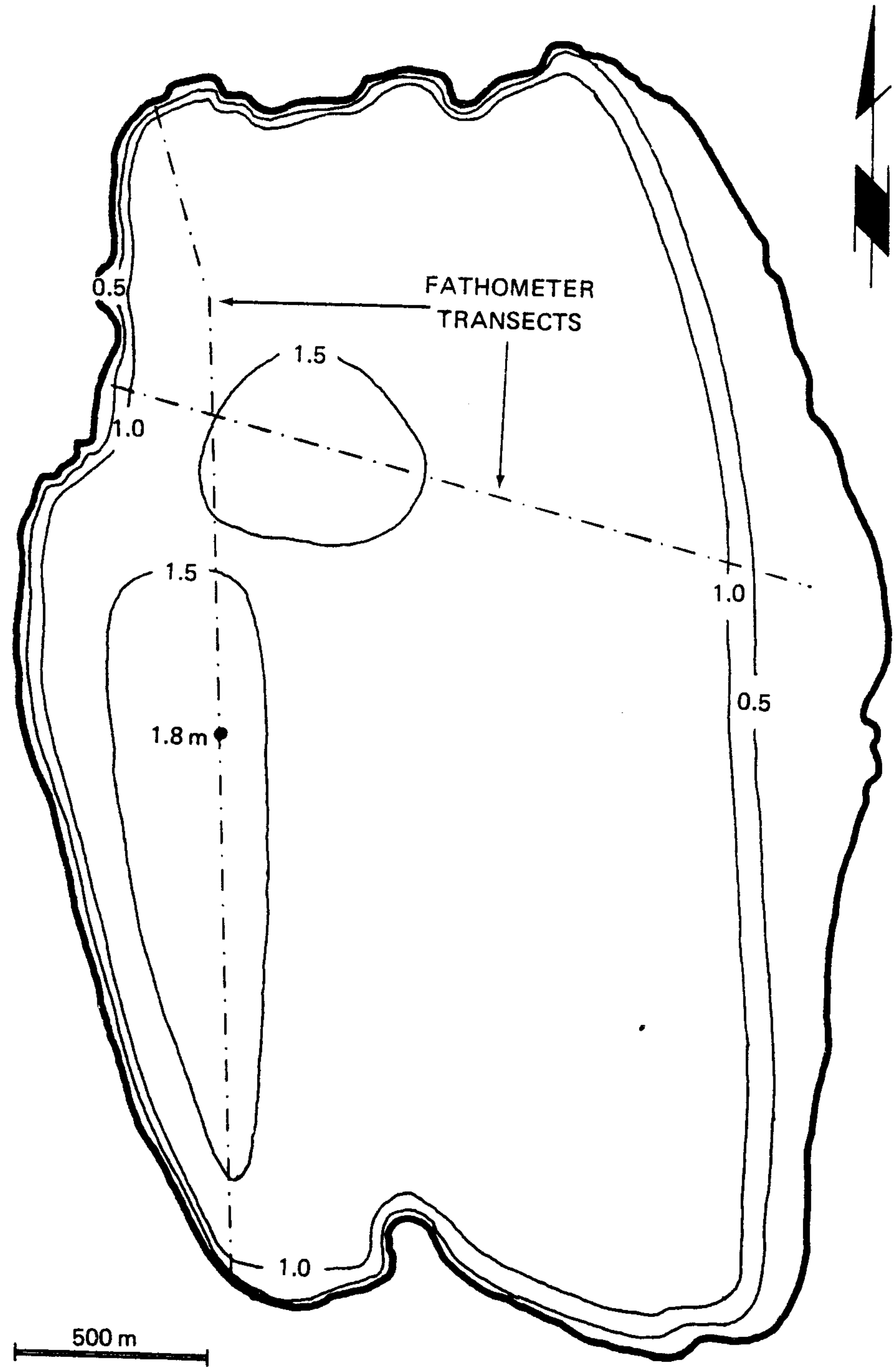


Fig. 21. Depth contours (m) in Lake SLAR-2.

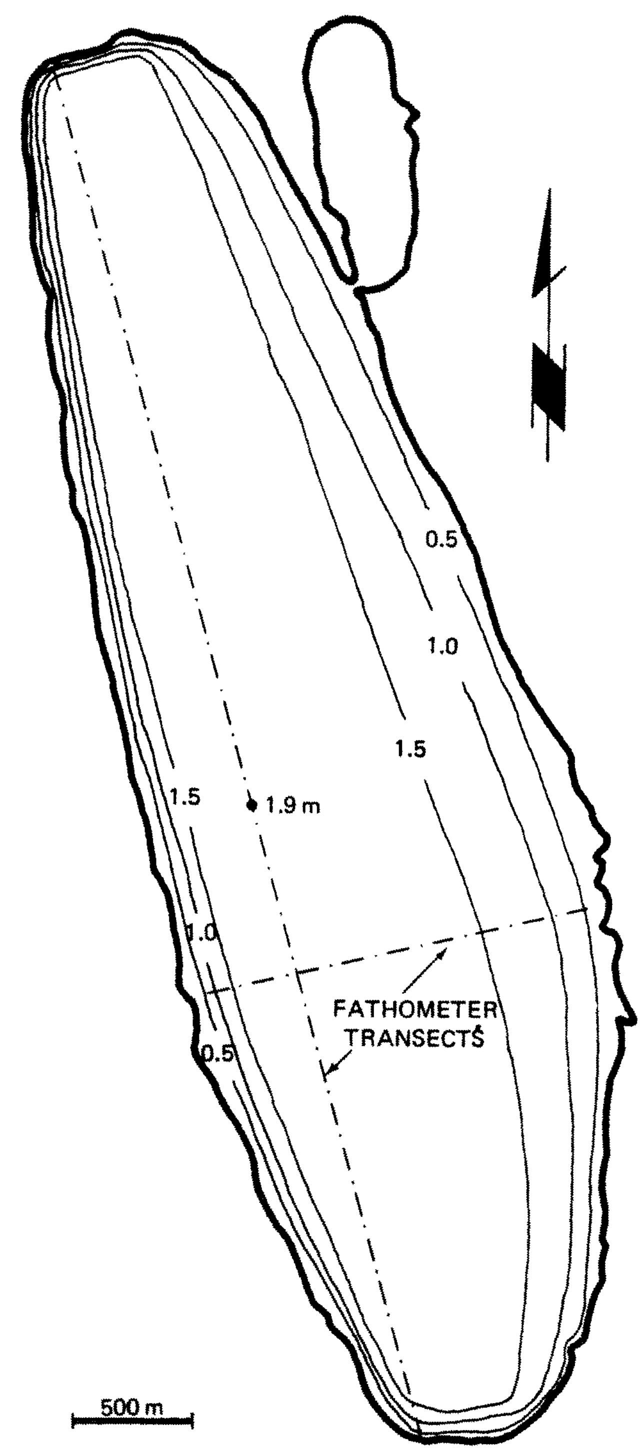


Fig. 22. Depth contours (m) in Lake SLAR-3.

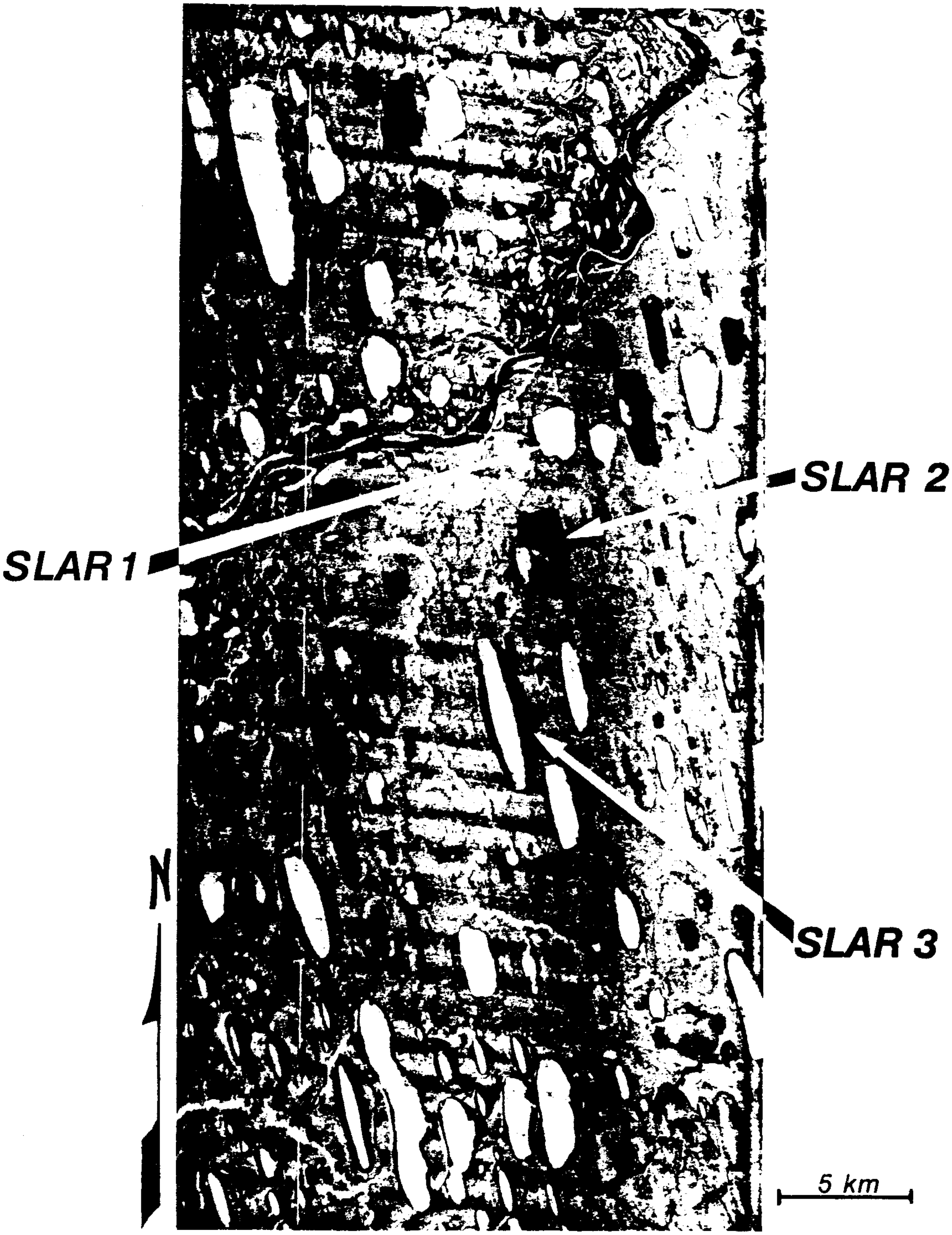


Fig. 23. SLAR image acquired over SLAR verification lakes SLAR-1, SLAR-2, and SLAR-3, 21 February 1979.

each lake in Figures 20-22, with the bright returns in Figure 23, show the close approximation of where liquid water exists below the 1.4 m thick ice sheet for lakes SLAR-1, 2, and 3. The dark lake perimeters in the SLAR image occur where the lakes were less than 1.4 m deep and where the ice was frozen to the lake bottom. The interface between the bright SLAR images and the dark perimeters defines the ice/substrate contact zone within each lake. The 1.4 m contour is very close to shore in SLAR-1, which has a bright SLAR image across the entire basin, except for a small black line on the eastern shore (Figure 23). SLAR-2 is just the opposite, with most of the basin frozen to the bottom except for a small area on the western shore. SLAR-3 lake bathymetry is between the 2 other lakes in depth. It has broad shelves and an elongate 1.5 m basin containing free water for most of its length. The eastern and western shelves and the northeastern bay are black on the image, indicating depths less than the 1.4 m ice thickness present over the deeper lake areas on 21 February 1979 when the image was acquired.

Figure 24 illustrates a series of sequential SLAR images of lakes SLAR-1, 2, and 3 relative to winter 1978-79 ice thicknesses. The SLAR images are in order of increasing ice thickness with a summer (14 August 1979) image on the left, representing the ice-free condition, and successive images with thickening ice cover during the winter of 1978-79. The curve for winter ice thickness (Figure 24, bottom) was developed using ice thickness data described in Chapter III.

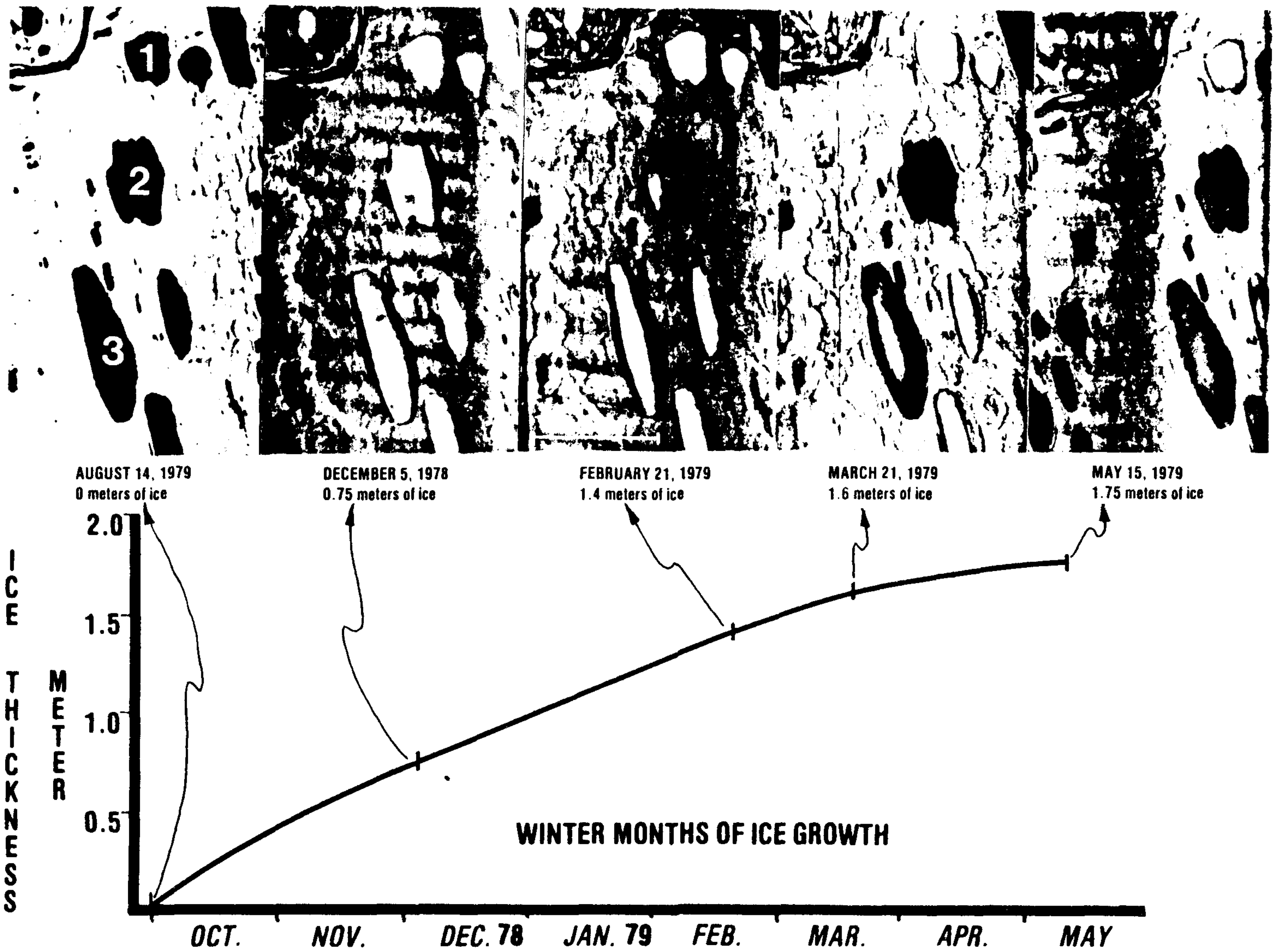


Fig. 24. Sequential SLAR images of lakes SLAR-1, SLAR-2, and SLAR-3 (top) correlated with ice thickness (bottom).

The 14 August 1979 image shows the lake numbers, SLAR-1, 2, and 3, superimposed on a black lake surface image. The lakes were free of ice; therefore, the radar energy was absorbed or was spectrally reflected away from the SLAR imaging aircraft by the water at the lake surface. The second image (5 December 1978) was acquired when the ice was about 0.75 cm thick. The image shows most of the surface on each lake as white because of high radar signal reflectance back to the aircraft. The shallow shelves on the eastern side of lakes 2 and 3 are black where the ice is frozen to the lake bottom. The third image (21 February 1979) was acquired when the ice was 1.4 m thick and was illustrated in Figure 23 and discussed above. The image of most of Lake 2 is black, indicating that ice was frozen to the bottom of 80 percent of the lake area. By 21 March 1979, when the ice was 1.6 m thick, Lake 2 was completely frozen to the bottom. Lake 3 had an elongate area in the middle that still had water beneath the ice. That area is white in the March image. The Lake 1 image is still almost totally white but has a small black area where the lake is frozen to the bottom on the eastern shore. The last image (15 May 1979) depicts both lakes 2 and 3 as black and totally frozen to the bottom with a 1.75 m ice thickness. The areas in lakes 2 and 3 that were greater than 1.75 m deep were too small to show significantly on the 15 May 1979 image. However, SLAR-3 has a subtle brightening of the SLAR image near the lake center. A thin layer of salty water, resulting from salt rejection and concentration, may still exist near the lake bottom, such that most of the SLAR signal is attenuated in the brine contaminated bottom ice rather than being reflected. The

Lake 1 image has a black perimeter, where the lake is frozen to the bottom, surrounding the deeper white mid-basin that is more than 1.75 m deep.

Each of these 5 images and corresponding ice thicknesses may be compared with Figures 20-22 to verify these interpretations. Comparison of summer bathymetric contours with Figure 24 images portraying contours interpreted by ice thickness, verifies that those images with lake areas that are dark are frozen to the bottom, and those that are white have free water beneath the ice cover. Nearly 200 holes were drilled in the winter ice cover during this study and also verified these findings. In every case, where a SLAR image had a bright return from a lake, water was found below the ice cover. Similarly, the lakes with bright centers and dark perimeters were found to be frozen to the bottom along the perimeter.

Lake SLAR-3 has been selected to illustrate the use of sequential SLAR images for contouring lake depths (Figure 25). The first 4 images shown in Figure 24 were enlarged and cropped, leaving only Lake 3 at the top of Figure 25. A zoom transfer scope was used to overlay each image on a shoreline map of the lake. The 0.0 m (shore), 0.75 m, 1.4 m and 1.6 m ice/substrate contact zone contours provided by the SLAR images were interpolated to obtain the 0.5 m, 1.0 m, and 1.5 m depth contours shown on the upper right. Fathometer profile data acquired on 2 summer (August 1979) fathometer transects were used to compare depth data with SLAR image interpretation. The fathometer transects made are shown on the 0.0 m or shoreline map (lower left). Each transect crossed a depth

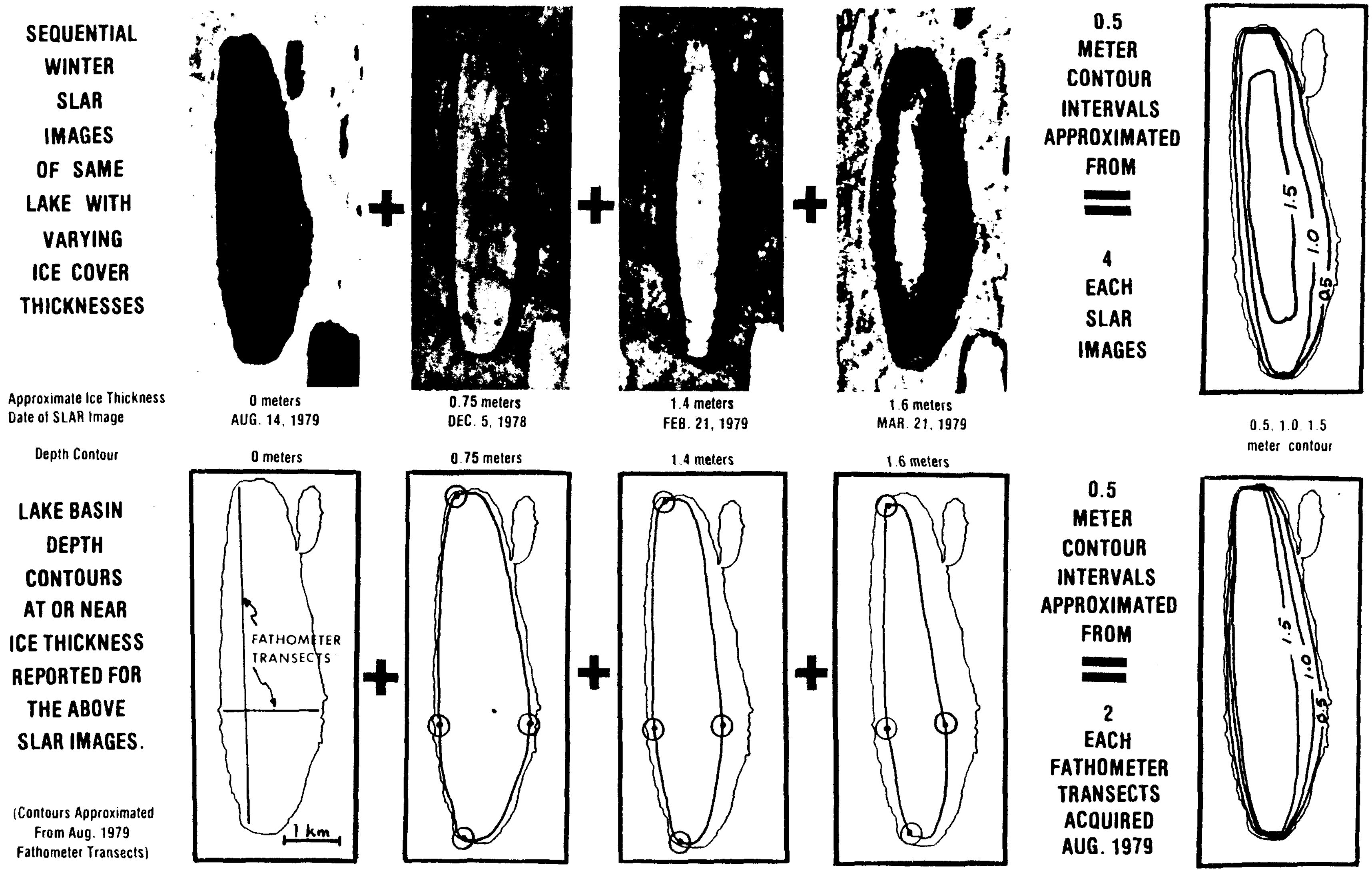


Fig. 25. Lake depth contour determination by 2 methods: (top) 4 sequential SLAR images with empirically derived ice thickness; (bottom) 2 summer fathometer transects.

interval twice, providing 4 points on the 2 transects from which a contour could be approximated. The 4 points were plotted, and the extrapolation of these points was used to estimate each contour. Contour estimates are shown for the depths (0.75 m, 1.4 m, and 1.6 m) corresponding to ice thicknesses in the above images. The final 0.5 m, 1.0 m, and 1.5 m contours estimated from the 2 fathometer transects are shown in the lower right in Figure 25.

The 2 methods provide slightly different results; however, both provide acceptable data for practical approximations of lake bathymetry and/or calculations of lake water volume. Both methods have some inherent error, but in this case more error undoubtedly exists in the fathometer transects. The largest margin for error for fathometer data is the few data points used to estimate a contour around an entire basin; however, more transects can be acquired to reduce this error with sufficient time and money. The 2-dimensional SLAR image eliminates this problem. Other potential fathometer data errors exist in transect position identification accuracy, consistency of aircraft speed across a transect, and accuracy of obtaining fathometer depths (± 10 cm). Methods for obtaining fathometer transect bathymetry are described in Chapter III methods.

The SLAR interpretation method for obtaining lake depth contours also had some error that was associated with accuracy of ice thickness determinations, resolution of the SLAR imagery (30 m), accuracy of contour placement utilizing zoom transfer scope overlays, and interpolation of desired contour intervals from the ice thickness intervals imaged on specific SLAR acquisition dates.

The advantage of the SLAR method over the fathometer transect method is that SLAR enables us to use remote-sensing imagery, with relatively few ground verification measurements of ice thickness, to obtain regional lake depth information. The major drawback of this method is that it is useful for obtaining depth contour information only to the maximum winter ice thicknesses achieved (≈ 2 m) and only for freshwater lakes. Because most arctic coastal plain thaw lake depths range from 0 to 2 m depth, this method has practical utility for assessing and/or inventorying lake depths when repetitive radar coverage of the area becomes economical. This may be imminent because use of Synthetic Aperature Radar (SAR) systems on Space Shuttle and/or future satellites has been proposed. The imagery from the Seasat Satellite SAR would have provided a good test had the system remained operational into the winter months. Better image resolution would also be beneficial for interpreting depth contours of small lake and pond basins.

Various SLAR Signal Reflections

Repeated SLAR coverage of the same lakes on the study transect provided the opportunity to study anomalies in the SLAR reflections. Subtle anomalies, not evident in a single image, became obvious in successive images. Poor SLAR image quality often caused image blemishes; however, system perturbations could be separated from signal reflection anomalies caused by lake bathymetry on successive images.

<u>Shallow (< 4 m) versus Deep (> 4 m)</u>. As the water depth increases within a basin, the capacity and water volume available for accepting the dissolved gases expelled from the water transitioning into ice cover also increase (see Chapter III - Ice Cores). A decrease in gas bubbles was observed in the 5 ice cores acquired from lake depths over 3 m. Cores from lakes B-1 and C-1 came from the ice cover over lake depths of 3.4 and 4.0 m, respectively. Both spherical and columnar bubbles existed but in lesser concentrations than found in shallower lake areas.

The 2 cores taken from the ice cover over deep Teshekpuk Lake areas had different SLAR signal returns. The core from the deepest area, 5.6 m, had no elongate bubbles and only small spherical bubbles at the surface within over-ice. This deep area had been chosen because of lack of strong SLAR signal return in an area known to be too deep to be frozen to the bottom. The other 2 Teshekpuk Lake ice cores were acquired in a shallower area (3.8 and 4 m), where the SLAR return was stronger. These cores had large (up to 0.5 cm diameter by 11 cm long) bubbles but very few when compared with those from shallow 1 to 3 m deep lakes. Vertical bubbles 3 cm or more long provide excellent radar reflectors for energy from the 3 cm wavelength X-band SLAR.

The ice cover over the shallow water of most thaw lakes contains an abundance of columnar bubbles capable of reflecting a SLAR signal (see Chapter III - Ice Cores). Lake areas sampled that were over 4 m depth had ice covers with few of these elongate gas bubbles. More ice cores from deep lake areas are needed to increase the sample size and confirm these observations.

The interpretations of dark versus bright returns on SLAR images over lakes basins has been described above. The proposed mechanism providing for this variation in radar signal return is illustrated in parts A and B of Figure 26. Part C illustrates an anomaly observed in imagery over lakes greater than 4 m deep. The physical mechanisms for the SLAR reflections have not been proven, but sufficient antithesis support and empirical data accumulation warrant discussion of hypotheses describing the radar signal interactions necessary to produce the SLAR images observed. Further specific investigations are necessary in order to describe the physics of radar signal mechanisms at the interfaces encountered. Each part of Figure 26 shows a hypothetical lake basin with the expected April SLAR image above a mid-lake cross section of lake depth, illustrating potential radar signal interactions with air, snow, ice, water, and soil interfaces.

Each lake cross section shows the interfaces crossed by the radar signal and an idealized path for the most significant portion of the incident radar energy. The radar signal first strikes the dry snow cover which is almost transparent to the radar signal (Campbell et al. 1975). The penetration or propagation of the radar signal depends upon changes in the dielectric constant and on the geometric size or roughness of the features being penetrated at an interface. The only interface with a large change in dielectric constant is the ice ($\approx$ 3)/water ($\approx$ 60) interface. Rapid changes in the dielectric constant and/or the presence of interfaces near to or larger than the signal wavelength (3 cm) will reflect the signal. The dielectric properties of ice, water, and soils

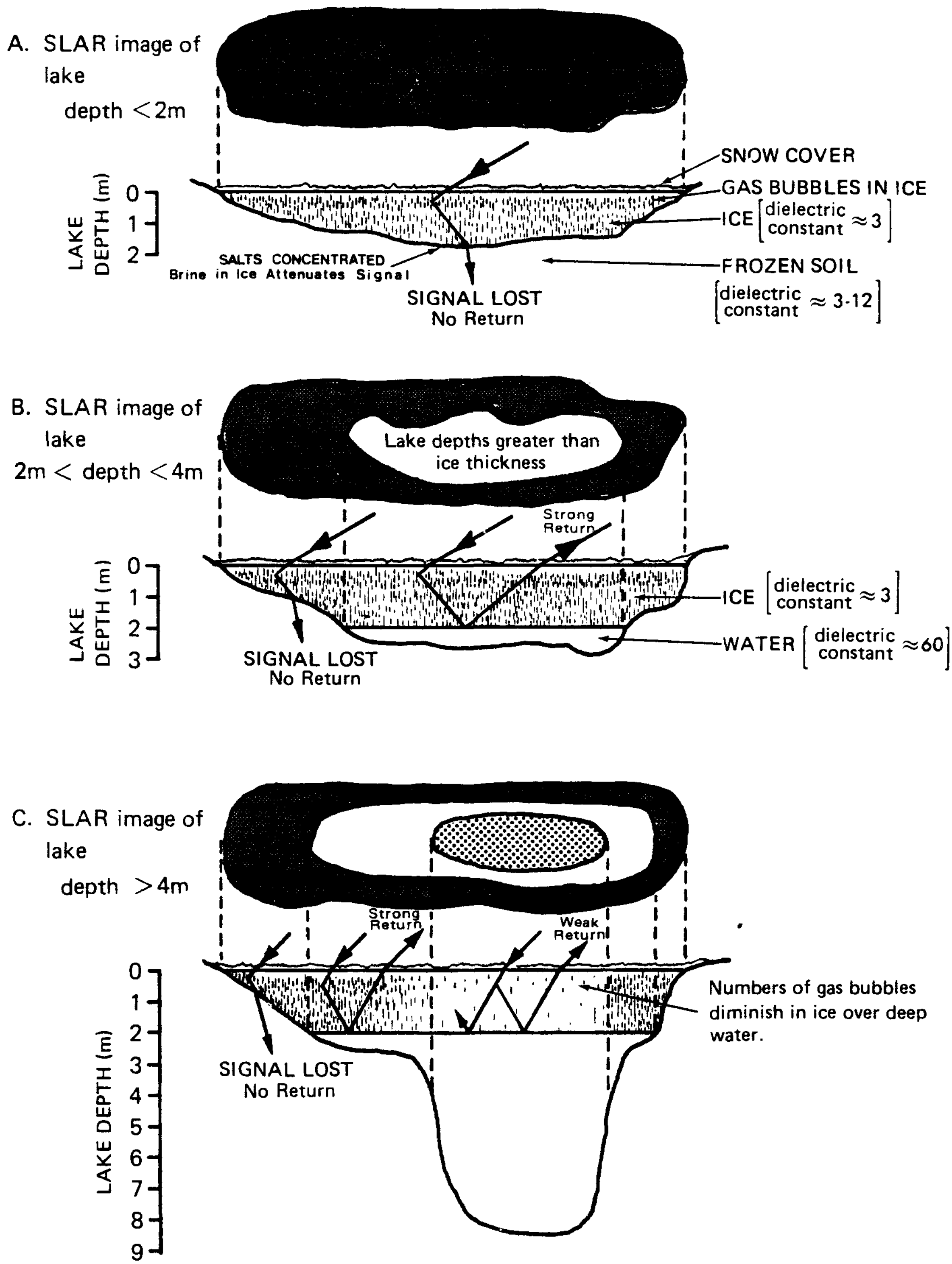


Fig. 26. Three hypothetical SLAR signal reflections within lake cross sections of various depths below respective illustrations of expected April SLAR images.

potentially penetrated by the radar signal have been reported and discussed in attempts to explain the arctic lake imagery (Arcone et al. 1979, Olhoeft 1977, Wong et al. 1977, Bryan and Larson 1975, Page and Ramseier 1975, Vant et al. 1974). Dielectric constants from these references have been reported in Figure 26 to help explain the penetration or reflection of the signal at an interface. The signal can be lost by reflection away from the receiver or by attenuation within a substrate. A 9.2 GHz signal can penetrate from 10 to 20 m of freshwater ice but is attenuated much more rapidly in water because the signal cannot penetrate 1 cm of water (Bryan and Larsen 1975). Page and Ramseier (1975) give a signal loss of 0.05 dB/m for the 10 GHz radar signal in freshwater ice.

The radar signal is capable of penetrating the air/snow/ice interfaces and can travel through 2 m of ice to reach the ice/water interface. The signal would be attenuated rapidly if it entered the water, but with an order of magnitude change in dielectric constant from ice ($\approx$ 3) to water ($\approx$ 60) the signal is reflected at this ice/water interface. The columnar bubbles, up to more than 12 cm long, provide a second perpendicular surface efficient in reflecting or scattering energy back toward the receiving antennae. The fact that the bubbles are elongate and vertically oriented provides for less omnidirectional scattering equal radial scattering, and more forward scattering and reflection toward the ice/water interface. This provides the potential for greater signal return to the receiver. The path taken by the signal is not as simple as that shown in Figure 26, because the signal may be reflected off or scattered from a multitude of ice/gas bubble interfaces, both on the way down to the ice/water interface and on its return trip up to the ice/air interface.

The concept of scattering off columnar bubbles merits an hypothetical description. The important aspect is that the vertical orientation of bubbles could retain signal angles so that upon re-emergence from the ice, a large portion of the signal's angle is equal to its angle of incidence. The single columnar bubble (Figure 27 Part A) provides symplistic proposed energy pathways. Most of the incoming energy is scattered downward and radially as shown. The signal cannot be scattered upward off bubbles, because bubbles contained in lake areas frozen to the bottom would provide a strong SLAR signal return, which does not occur. The downward scattered signal needs a second reflecting interface that is perpendicular to the bubbles (i.e. the ice/water interface) to return the signal. Specular reflection off the ice/water interface returns the energy at an angle (θ_2) equal to the incident energy (θ_1). Without the bubbles the signal would be specularly reflected off the ice/water interface away from the aircraft. This would give a dark image as seen in deep lakes (> 4 m) where few columnar bubbles exist in the ice cover. The requirements for a strong signal return and bright SLAR image are an ice cover with many columnar bubbles and an ice/freshwater interface (Figures 26 Part B and 27). The majority of such a signal return could best be described 3-dimensionally as an inverted cone with the cone's surface at the same angle as the transmitted signal (Figure 27 Part C). Thus, the signal

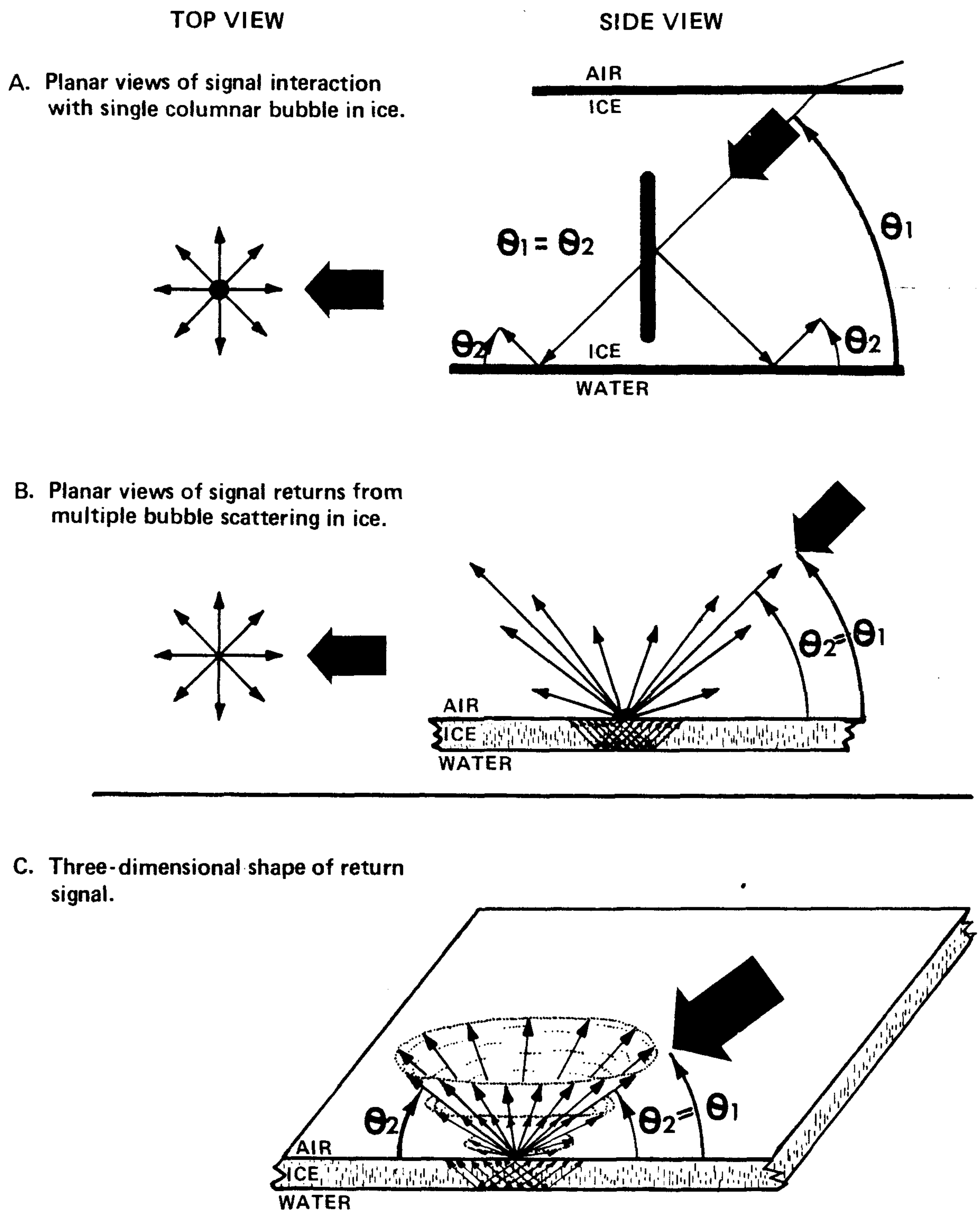


Fig. 27. Hypothetical SLAR signal scattering off columnar gas bubbles and from ice cover containing these bubbles.

expected to return via equal refraction upon entering and departing the ice and from reflection/scattering off bubble and ice/water interfaces nearly perpendicular to each other should be much greater than expected from most natural substrates that scatter the signal omnidirectionally or have less perpendicular reflecting interfaces.

Figure 26 Part A illustrates the condition where a lake basin is completely frozen to the bottom, providing a weak signal return or dark SLAR image. The ice on shallow (0 to 2 m) lakes has many gas bubbles that reflect/scatter the signal but has no reflecting interface below the ice to provide the second reflective surface. The dielectric constant of ice ($\approx$ 3) and frozen soil ($\approx$ 3-14) are similar, allowing the signal to continue into the ground with little to no return to the receiver. A bottom substrate particle, although in a frozen matrix, may have a very thin unfrozen film of water adsorbed to its surface that attenuates the SLAR signal.

Another condition might prevent the return of the SLAR signal in shallow lakes. Salts concentrate rapidly in shallow lakes as the ice nears the lake bottom. The thin salty layer of water inhibits complete rejection of salt from the ice matrix. Salts retained in the ice are in the form of liquid brine cells between ice crystal platelets. The brine cells can attenuate most of the SLAR signal, resulting in a dark image when underlying lake water is $\geqslant 2°/_{\circ\circ}$ salinity.

Figure 26 Part B has the shallow condition similar to Part A around the lake perimeter, but the interior lake basin has water beneath the ice. The ice on lakes up to 4 m deep was observed to have numerous columnar gas bubbles, sufficient to reflect most of the signal; however, here the ice/water interface had an order of magnitude change in dielectric constant, reflecting the signal back to the surface and the receiver.

Part C incorporates conditions described for B and A plus a third subtle condition that has been observed in several of the lakes studied. The large stiple in the lake center of Part C represents SLAR image gray-tones that are darker than the bright returns from the shallow areas (< 4 m) with water below the ice yet lighter than areas frozen to the bottom (< 2 m). Four meters was not a precise depth at which this occurred, but the phenomenon occurred in areas > 3 m depth within study lakes B-1 and C-1 and for 1 of 2 points ⩾ 4 m compared within Teshekpuk Lake. The ice cores compared between the 2 Teshekpuk Lake stations had different bubble contents. A few columnar bubbles were observed in the ice core over the shallower station (4 m), which gave a moderately bright SLAR image, whereas no elongate bubbles were found in the ice core acquired over the deeper station (5.6 m), which gave a darker SLAR image. The center and western half of the Teshekpuk Lake SLAR image had intermediate gray-tones, indicating depths > 4 m. The image from the southern half of Lake C-1 (Figure 16) is darker over the deepest (> 3 m) lake area (Figure 8). Similarly, the 2 deep areas (> 3 m) in B-1 (Figure 5) are slightly darker in SLAR imagery (Figure 15) than the adjacent mid-depth areas (1.4 to 3 m) but are lighter than the shallow (< 1.4 m) areas frozen to the bottom. The signal is specularly reflected off the ice/water interface, but without bubbles there is no second interface to return the signal to the receiver. Few bubbles are expected in ice when sufficient water exists below the ice to accept the gases rejected from the ice without becoming saturated. Few ice cores were acquired, but each substantiated this hypothesis.

Specific Conductance. The salt content of the water beneath ice cover influences the SLAR signal reflection at the ice/water interface. As the salinity of the water approaches 1°/₀₀ (≈ 1,600 μmhos) the newly forming ice traps salt in liquid brine cells incorporated in the ice matrix. The signal attenuation due to the increased water content in the ice is increased 2 to 3 orders of magnitude to 5 to 70 dB/m (Weeks et al. 1978). Weeks et al. state that there is insufficient penetration of the signal through this brine-contaminated ice layer to provide a return signal from the ice/water interface. Water content within the ice matrix is sustained by the brine thus attenuating the radar signal rapidly. This phenomenon was confirmed by comparing salinity increases in Imikpuk Lake (A-1) with the sequential SLAR images acquired throughout the winter of 1978-79. The salinity increased from 0.5°/₀₀ (840 μmhos) in August 1978 to 2°/₀₀ (3,160 μmhos) in May 1979. The A-1 ice cover over water became increasingly difficult to discriminate in successive SLAR images later in the winter season as gray-tones became darker due to increased salinity; however, the ice frozen to the bottom could still be distinguished from ice over the deeper A-1 basin in a 15 May 1979 image. The 21 February 1979 SLAR image (Figure 14) shows Lake A-1 when the salinity was 1.3°/₀₀. The return from A-1 was not as bright as from A-2, but it is stronger than A-3, which is frozen to the bottom and is brighter than the salt water lagoons with salty water beneath ice covers immediately up and down the coast from A-1. The gray-tones caused by increased salinity can usually be differentiated from those caused by lack of bubbles in deep lakes. Increased salinity causes the same gray-toned image throughout the entire portion of the basin not yet frozen to the bottom. On the other hand, both bright and gray-tones exist in the unfrozen areas of deep lakes, because dark images over areas frozen to the bottom, grade into bright images in shallows (with columnar bubbles) not yet frozen to the bottom and finally into gray-tones over the deeps (lacking columnar bubbles).

Repetitive images over a lake remove even more of the potential for mistaken interpretation of gray-tones seen in April lake images. Early images (November-January) of $\approx$ 2 m deep areas are bright because salts have not been concentrated sufficiently to cause image gray-tones; however, the images darken with time as salts concentrate. The reverse time sequence occurred over deep areas. The images of lake areas > 3 m deep are darkest and largest early in the freezing season. These areas become smaller and brighter with time as the ice thickens and additional bubbles are incorporated in the ice cover, causing more SLAR signal return particularly from the 3 to 4 m deep areas.

Some care must be taken in SLAR image interpretation where the image is dark with subtle brightening near the lake center. The lake may be shallow and almost frozen to the bottom, but may still have a salty water layer below ice with sufficient brine contamination in the ice to attenuate most of the SLAR signal.

<u>Other SLAR Signal Returns from Lakes</u>. Melting of ice affects SLAR signal returns much like an increase in salinity. As the water content of the ice increases, the signal is attenuated and the images of lakes darken. The final SLAR imagery of winter 1979 ice covered study lakes was acquired on 5 June. Melt conditions varied: some lakes in Area C were completely melted; lakes in Area B had large moats surrounding them; and "A" lakes had most snow melted but little to no moat formation or puddling. Water content of the ice, however, was sufficient to prevent return of any SLAR signal from all study area lakes because of specular reflection and absorption of the signal. All lakes from the southern to the northern end of the transect were black on the 5 June imagery. The image brightness for ice covers not frozen to the bottom decreased to the south in imagery acquired on 15 May 1979. No melt had begun on "A" lakes, but snow was gone from "B" lakes and melt had begun on "C" lakes.

Aircraft ice landing strips returned 2 different runway images, depending on the size of the area cleared of snow and methods used to deposit the snow removed. Snow that is piled or ridged, leaving sharp scarps, reflects the radar signal well. An example of this is the ice landing strip on two-thirds of the length of Lake A-3 with a parking apron at the southern end shown in Figure 14. Scarps are also created when tractors compress snow under their tracks leaving steep snow escarpments that reflect the SLAR signal (Mellor, 1980). Winter tractor trails are visible in the Figure 14 image below Lake A-3 and from Barrow down to the lower left side of the image. The trail below Lake A-3 continues to the east and bends to the south, terminating at another airstrip immediately adjacent to the edge of the image. This airstrip had a wide runway free of snow when this image was acquired. The snow that had been removed was piled adjacent to the runway. The result on the image was a bright area for most of the lake from escarpments created by snow removal equipment except for a dark image down the snow free runway.

Ice ridges that occur primarily on large lake basins can reflect a large portion of the SLAR signal, creating a bright line on the image. Ice ridges begin to form during mid-winter fluctuations in ice temperature. A rubble pile of ice is created in zones of weakness where cracks have formed because of thermal expansion and contraction of the ice. The ice ridges grow substantially with rises in temperature in March and April, and then become more apparent in SLAR images. An example of a pressure ridge < 1 m high in the February image (Figure 14) may be seen at the northern end of Lake Sungovoak located near where "Lake" is printed on the map in Figure 11. Teshekpuk Låke ridges, measured to 4 m high and 30 km long, appear very bright on April 1979 images.

The locations of over-ice areas (see Chapter III - Over-ice) were documented on several lakes to determine if over-ice affected SLAR signal reflections. SLAR images had no interpretable anomalies in the vicinity of over-ice. The dimensions of gas bubbles observed in over-ice were 5 mm or less, too small to reflect a 3 cm wavelength radar signal.

SUMMARY

Ice thicknesses throughout the 1978-79 winter season (Chapter III) were measured and documented across the study transect from Barrow to the Brooks Range and were used to interpret SLAR imagery over the same area. SLAR images from shallow Alaskan arctic lakes not frozen to the bottom are bright compared with brackish and deep arctic lakes or non-arctic lakes.

SLAR is a particularly well-adapted tool with which to obtain regional lake depth information because of unique environmental conditions that exist for Arctic Coastal Plain lakes. The SLAR system is not inhibited by lack of winter sunlight or the persistent fog and cloud cover. It performs best for aquatic survey in this flat terrain where terrain distortion and slant signal shadows are of no consequence. The characteristically shallow lakes (< 4 m) have thick ice covers with columnar bubbles and an ice/water interface which return the SLAR signal well in lake areas with fresh water beneath the ice. Because there are so many lakes and because they can change rapidly in area and depth, a means such as SLAR is needed for efficient repetitive regional assessment of lake area and depth.

Three different SLAR signal returns provide depth information on images of the lakes studied. A bright image was obtained from areas where there was fresh water beneath the ice cover in a lake ≤ 4 m deep. A dark image was obtained from a lake that was either frozen to the bottom or had water beneath the ice with a salinity $> 2‰$. Intermediate gray-tones occurred in a lake image where water beneath the ice was > $1°/_{oo}$ and ≤ $2°/_{oo}$ salinity or was in a lake area > 4 m deep. Some potential exists for discriminating between gray-tones caused by salinity and those produced by > 4 m lake depths, but SLAR image blemishes and resolution complicate this problem.

The ice cover/lake bottom contact zone can be interpreted from the SLAR image of a lake. This interpretation plus ice cover thickness for the image date provide an approximation of the lake depth contour at that ice thickness. Sequential SLAR imagery over a lake basin in conjunction with ice thickness information over the winter ice growth season can be used to estimate isobaths down to the limit of maximum ice growth. A depth contour at about 4 m may also be determined with the aid of SLAR images. I hypothesize that columnar bubbles that reflect the signal in the ice cover at < 4 m lake depths are fewer in number at lake depths > 4 m, causing the bright SLAR image from shallow water to grade into gray-tones at lake depths ⩾ 4 m. April was determined to be the best month to acquire SLAR imagery of Alaskan arctic lakes to define isobaths and winter water sources at near-maximum ice thickness.

CHAPTER III

SURVEYS FOR VERIFICATION OF LAKE CONSTITUENTS/ BATHYMETRIC ASSOCIATIONS

INTRODUCTION

Chapter II describes SLAR as a remote-sensing tool capable of mapping water depths. The significance of this tool is based on our ability to relate aquatic resources to mappable water depths. The objectives of this chapter are to identify and verify lake characteristics associated with water depth and trends of regional change that are distinct from characteristics common to all these lakes. This information can be used to aid land managers, industry specialists, and scientists in identifying specific aquatic resources, their locations, and areas of significant regional concentration.

The descriptive literature on the Alaskan arctic has become voluminous in the last 5 years. Several limnological reviews (Sater 1961, Livingstone 1963, Kalff 1970, Hobbie 1973) have provided broad essays on Alaskan arctic limnology. Zhadin and Gerd (1961) have done work in the Russian "Arctic Lake Region." The amount of published data has grown substantially since these reviews, primarily as a result of Outer Continental Shelf Environmental Assessment Program (OCSEAP) and International Biological Programs (IBP) Tundra Biome directed research (Hobbie 1980). Data available in the literature were not adequate to analyze constituent/depth relationships, thus requiring a study plan that sampled specific depths and regional morphologic and climatic variations.

Most Alaskan arctic lakes are shallow (1-3 m). Winter lake ice formation of approximately 2 m thickness controls biological activity so much that it is of major importance in predicting aquatic resources within a water body. Lakes frozen to the bottom cannot support overwintering fisheries. Many lakes that do not freeze to the bottom have less than 1 m of free water beneath the ice. These lakes often have restricted space, high concentrations of dissolved salts, and/or low quantities of dissolved oxygen. All of these may limit populations.

The winter ice cover has a dramatic influence on the heat budget of arctic lakes because much of the summer sun energy that reaches the lake surface is used to melt this ice cover, keeping summer water temperatures low. Thin ice cover on ponds is the first ice to melt in arctic basins. Shallow water can be warmed significantly in the summer (17°C temperatures have been recorded). The last ice to melt during spring break-up is the floating ice on large, deep lakes. Deeper (> 5 m) lakes seldom achieve temperatures higher than 10°C nor much thermal stratification.

The basin morphology of Alaskan arctic lakes is a result of the history of their formation. Three basic processes are evident in the formation. Most of the lakes in the foothills of the Brooks Range are of glacial or tectonic origin. They have basins up to 50 m deep (Hobbie 1962). Oxbow lakes are remnant sections of river channel. They are found adjacent to most of the major arctic rivers and are seldom deeper than 3 to 6 m. Shallow thaw lakes and ponds are the major aquatic feature across the Arctic Coastal Plain. They are caused by a combination of events but mostly by the melting of permafrost. The freezing of melt water into cracks in permafrost creates ice-wedge ridges in polygonal patterns. The low centers within the polygons often trap water to form marshy ponds. These 10 to 15 m diameter ponds, < 0.5 m deep, are common on the Arctic Coastal Plain (Britten 1966). The thawing of ice-rich permafrost below these ponds can unite and deepen the small ponds to form shallow thaw or thermokarst lakes (Black and Barksdale 1949, Rex 1961); however, regional geology also seems to play an important role in lake basin morphology. Sand dunes west of the Colville River, described by Black (1951, 1964), Walker (1967, 1973), Williams et al. (1977), and Carter and Robinson (1978), contribute to the formation of lake basin morphology and drainage patterns. Most thaw lakes are less than 5 to 6 m deep, but some Arctic Coastal Plain Lakes may be as deep as 15 m.

Although most of the lakes are shallow, they can be quite extensive in area, are elliptical, and have obvious axis orientation. Some near the Arctic Coast are as large as 12 x 4 km. Trends toward deeper basins, less axis orientation, and less surface area occur in lakes located to the south, away from the coast of the Arctic Ocean. A number of investigators have discussed methods of thaw lake origin and orientation of axes (Black and Barksdale 1949, Mackay 1956, Carson and Hussey 1960, Livingstone 1963). Although there is agreement that origin is based upon subsidence due to thawing of ice-rich sediments, the shape and orientation of lake basins may be due to several factors (i.e. wind generated circulation patterns, eolian sand formations, and other geomorphology).

From examination of ice-wedges under very shallow thaw lakes, Black (1964) suggested that the lakes could not be more than a few hundred years old, while lakes that have thawed out deep basins may be many thousands of years old. The Arctic Coastal Plain is in a continual process of dynamic hydrologic change, with some lakes losing surface area by draining while others are forming, enlarging, and coalescing.

Very little accurate or detailed lake depth data exist for the North Slope. A few assessment surveys (Holmquist 1975, Sloan 1977) have provided some single point mid-lake depths throughout the Arctic Coastal Plain. Petroleum exploration drill site assessments (Mellor et al. 1978, Reynolds et al. 1979) have provided some recent lake depth contours and other data throughout the National Petroleum Reserve-Alaska (NPR-A). The oil industry needs large quantities of freshwater for civil construction and drilling during the winter. The limited lake water between the bottom of the ice and the lake substrate is important for both the aquatic ecosystem and industry. Knowledge of the extent of aquatic habitat at different water depths can contribute to better management of the existing habitat, as well as utilization of the water it contains.

The North Slope lacks perennial ice because of its arid climate. Glacial activity is absent, but water is not. The area is unique among deserts, as it has well-developed river basins and an abundance of lakes and freshwater (Davies 1974). This surface water is held in a rather delicate balance due to low precipitation replenishment. The surface water results from: low runoff in terrain of little relief, lack of percolation into soil because of the permafrost boundary, and little evaporation due to summer fog and winter ice cover. Davies suggested that man would do well to respect this delicate balance before attempting to withdraw or change surface water for his needs.

Lakes cover from 10 to 50 percent of the terrestrial environment (Sellmann et al. 1975b). Yet, even more of the area can be considered wetlands, because much of it is ponds and marshes. The snow melt produced during spring break-up is trapped at the land surface. The ubiquitous standing water over the Arctic Coastal Plain has led to a controversial "wetland" issue among governing agencies. Most of this plain either has ponds or lake basins or shows evidence of past lake basins that have been drained, leaving a palustrine or wetland environment.

Although almost 100 percent of the Arctic Coastal Plain has sufficient summer surface water to be categorized as lake, pond, or wetland (Cowardine et al. 1979), the character of this area is altered by winter freezing. Complete ice and snow cover provide a surface that has a terrestrial rather than aquatic character for 9 months of the year.

Agency responsibility for the aquatic resources discussed varies, is poorly defined in some cases, and is constantly changing along with land ownership status. The Alaska Water Quality Management Planning

Program (1977) lists the following agencies as participants in the protection, management, monitoring, and assessment of North Slope lands and resources: Local - residents, villages, the North Slope Borough, the Arctic Slope Regional Corporation; State - The Trans-Alaska Pipeline Commission, Alaska Department of Natural Resources, Alaska Department of Environmental Conservation, Alaska Department of Fish and Game, and Alaska State Troopers; and Federal - U.S. Department of the Interior (Geological Survey, Bureau of Land Management, Fish and Wildlife Service, National Park Service), the U.S. Coast Guard, and the U.S. Army Corps of Engineers. Federal, state, and local agencies share and overlap significantly in the management and protection of this area.

METHODS

Lake Bathymetry and Constituents Sampled

A variety of physical, chemical, and biological measurements were taken at each of the 9 lakes. Constituents that might be affected by water depth were sampled at preselected depth intervals similarly for all lakes. Field-sampled constitutents are listed in Table 2, including data taken in 1978, 1979 and 1980. Figures 28 through 36 illustrate, for each of the 9 study lakes, the lake bathymetry with the stations sampled, their location within the lake basins, and the depth of water in which samples were taken. Symbols are used to condense the sample information. The key to the symbols is in Table 2.

Table 2. Constituents sampled during 1978, 1979, and 1980. Station and transect locations within each lake are depicted in Figures 28-36 with the symbols adjacent to each constituent in this table.

SYMBOLS	CONSTITUENTS
	5-25 August 1978
—·—·—·—·— DEPTH 78	Fathometer transects
	Chlorophyll *a*
• CHL*a* 78	Water column
▽	Benthic gravity core
• ZOOP	Zooplankton net tow
78	Fish (gill nets in lake or traps near shore)
□ 78	Water quality station
	Specific conductance Secchi disc Nutrients (NH_3, NO_3, NO_2, Si and PO_4) Suspended sediment load Surface Temperature
	November 1978 to May 1979
○	Ice thickness (including snow thickness, freeboard, and water depth)
◯	Ice core
△ 79	Water quality station
	Dissolved oxygen Specific conductance
	7-20 August 1979
—·—·—·—·— DEPTH 79	Fathometer transects
	Chlorophyll *a*
	Florometer (*in situ*)
— — — — — — — FLORO	Surface transects
• V FLORO	Vertical profiles
• CHL*a* 79	Water column
⬠ CHL*a*	Benthic-Ekman Dredge

Table 2. Continued.

SYMBOLS	CONSTITUENTS
	Primary Production ^{14}C
• ^{14}C 79	Water column
^{14}C	Benthic-Ekman Dredge
INV	Benthic Invertebrates-Ekman Dredge
VEG	Vegetation transects
79	Fish (gill nets in lake or traps near shore)
□ 79	Water quality station Specific conductance Light Meter Nutrients (NH_3, NO_3, NO_2, Si, and PO_4) Suspended sediment load Surface temperature pH Alkalinity
7-15 April 1980	
⊙	Ice thickness (including snow thickness, freeboard, and water depth)
△ 80	Water quality station Dissolved oxygen-meter Temperature profiles Specific conductance Chlorophyll *a*-Water column Nutrients (NH_3, NO_3, NO_2, Si, and PO_4)

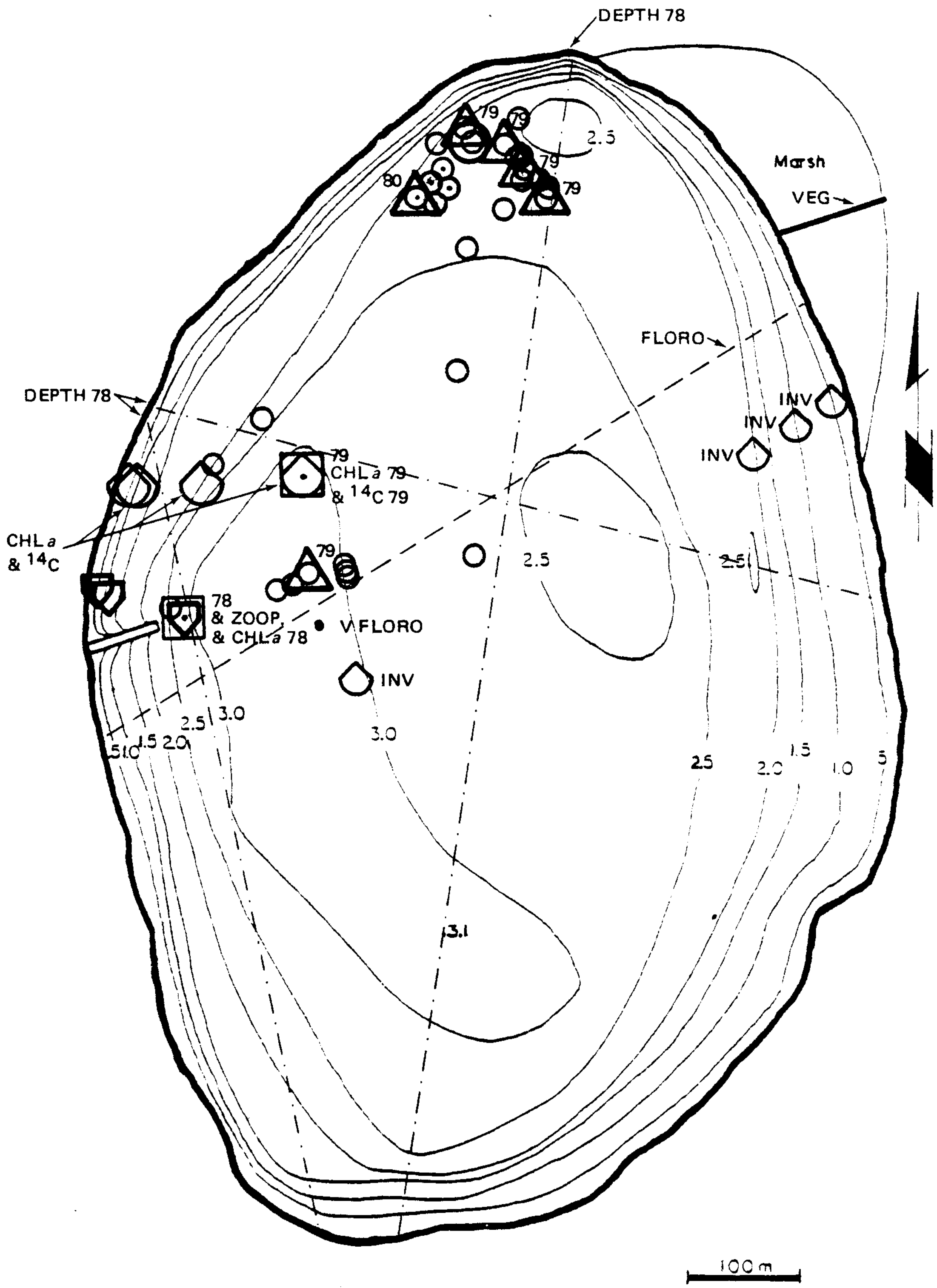


Fig. 28. Depth contours (m) plus stations and transects sampled in Lake A-1, Imikpuk. (Table 2 gives key to symbols).

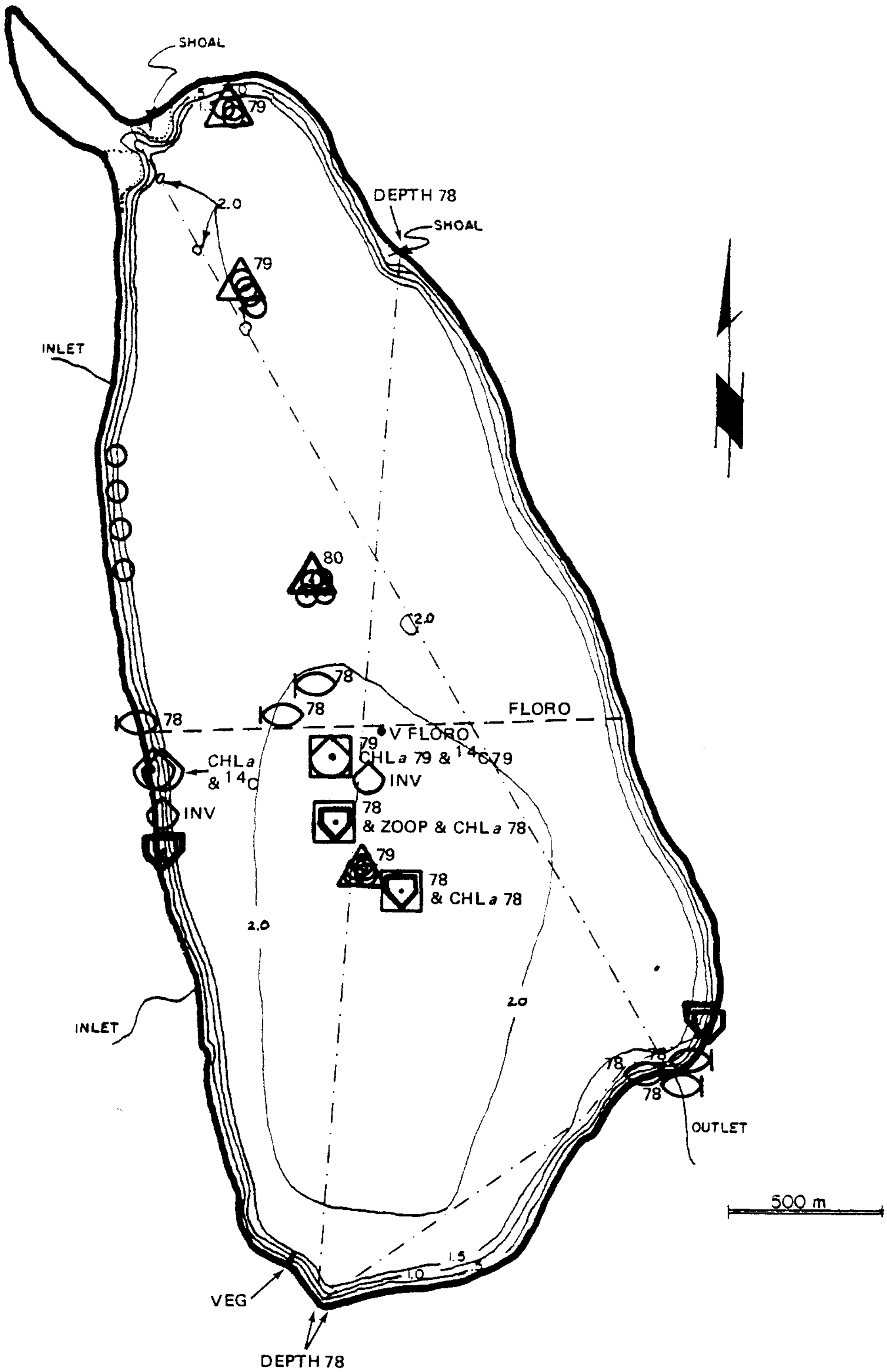


Fig. 29. Depth contours (m) plus stations and transects sampled in Lake A-2, Ikroavik. (Table 2 gives key to symbols).

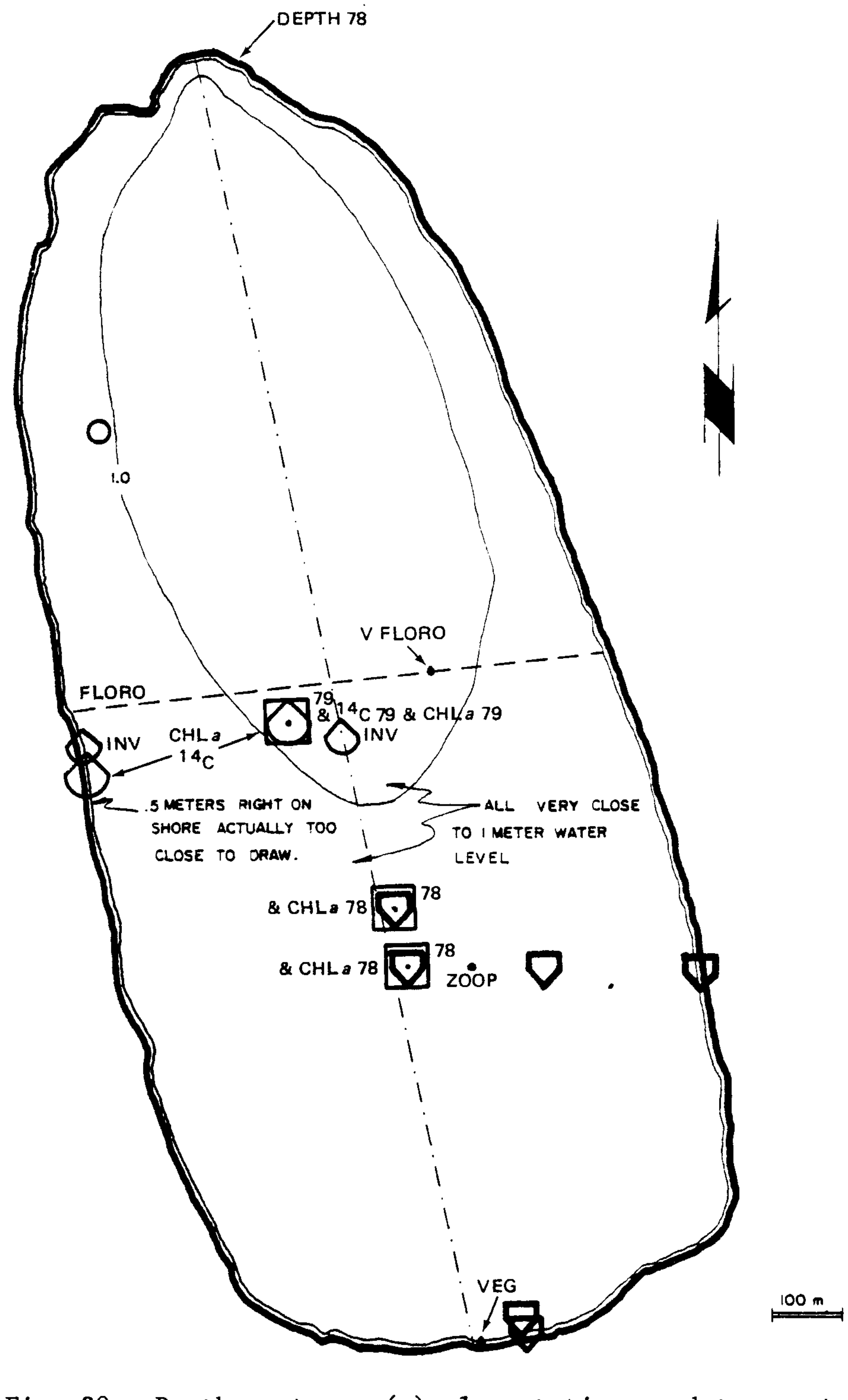


Fig. 30. Depth contours (m) plus stations and transects sampled in Lake A-3, West Twin. (Table 2 gives key to symbols).

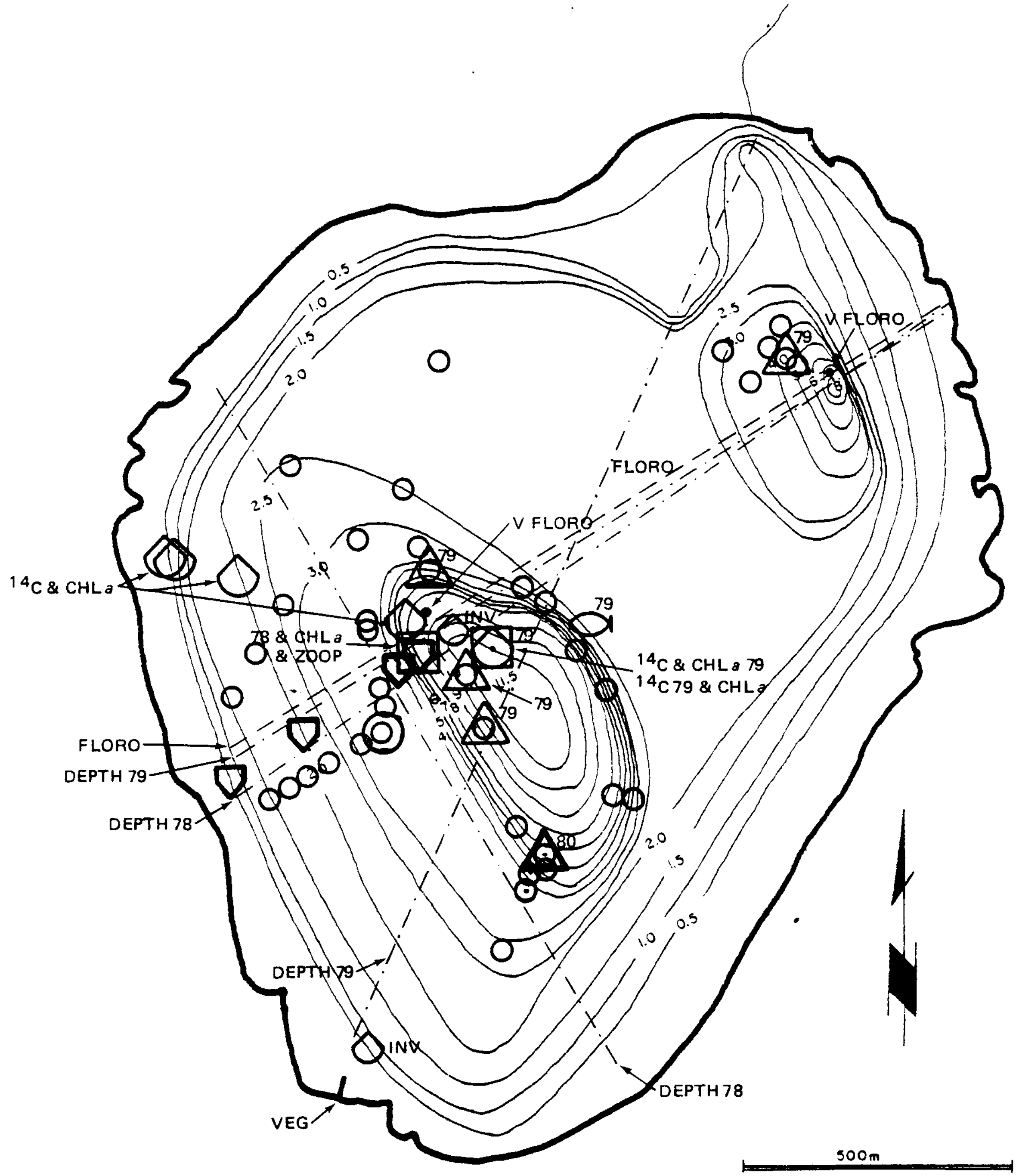


Fig. 31. Depth contours (m) plus stations and transects sampled in Lake B-1. (Table 2 gives key to symbols).

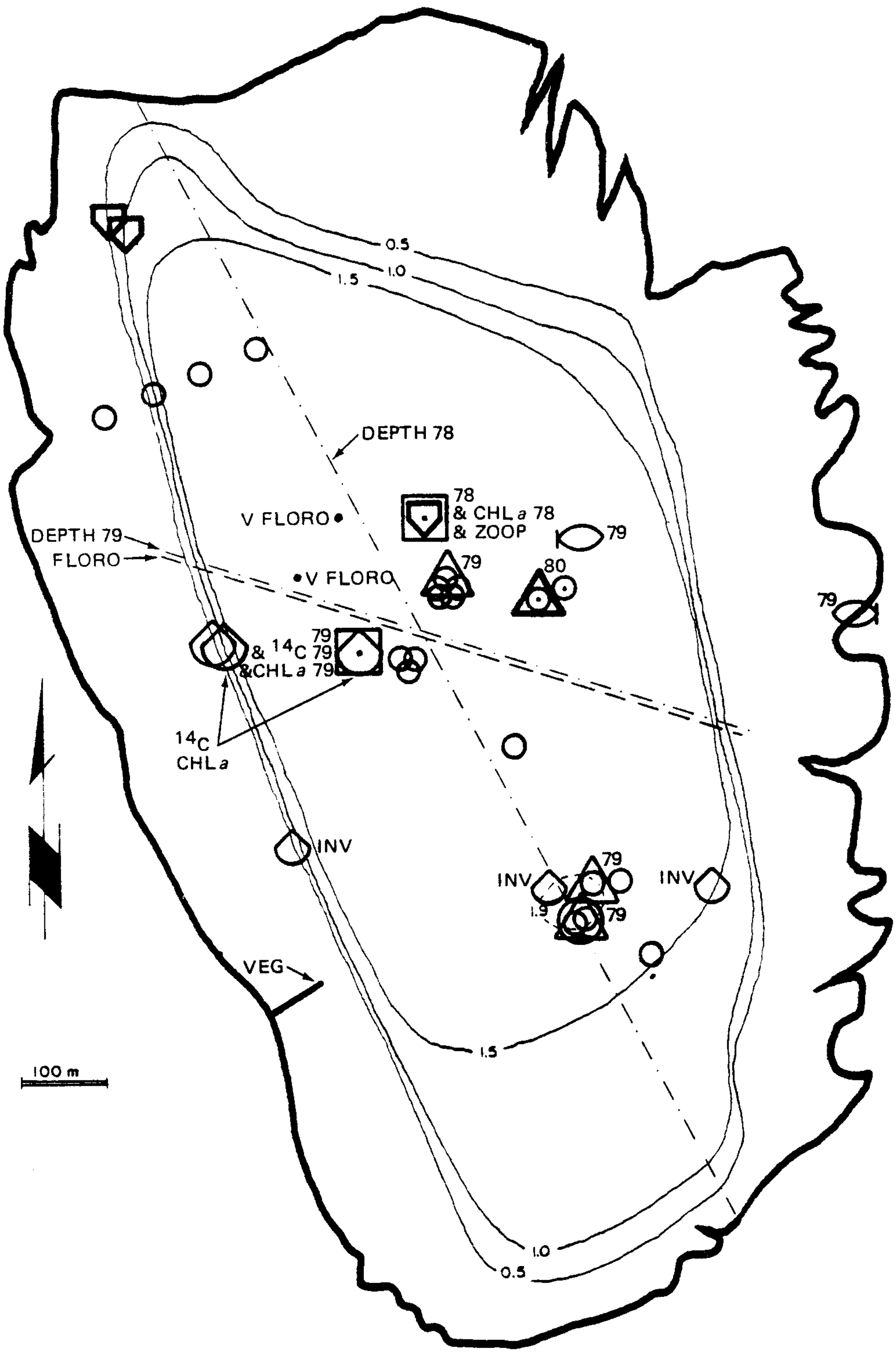


Fig. 32. Depth contours (m) plus stations and transects sampled in Lake B-2. (Table 2 gives key to symbols).

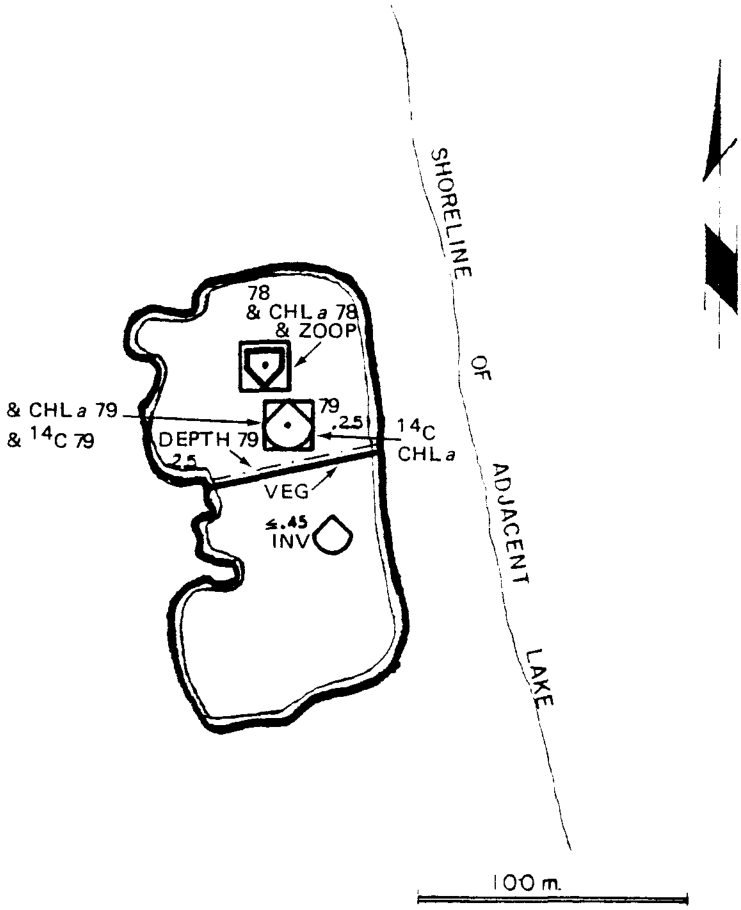


Fig. 33. Depth contour (m) plus stations and transects sampled in Pond B-3. (Table 2 gives key to symbols).

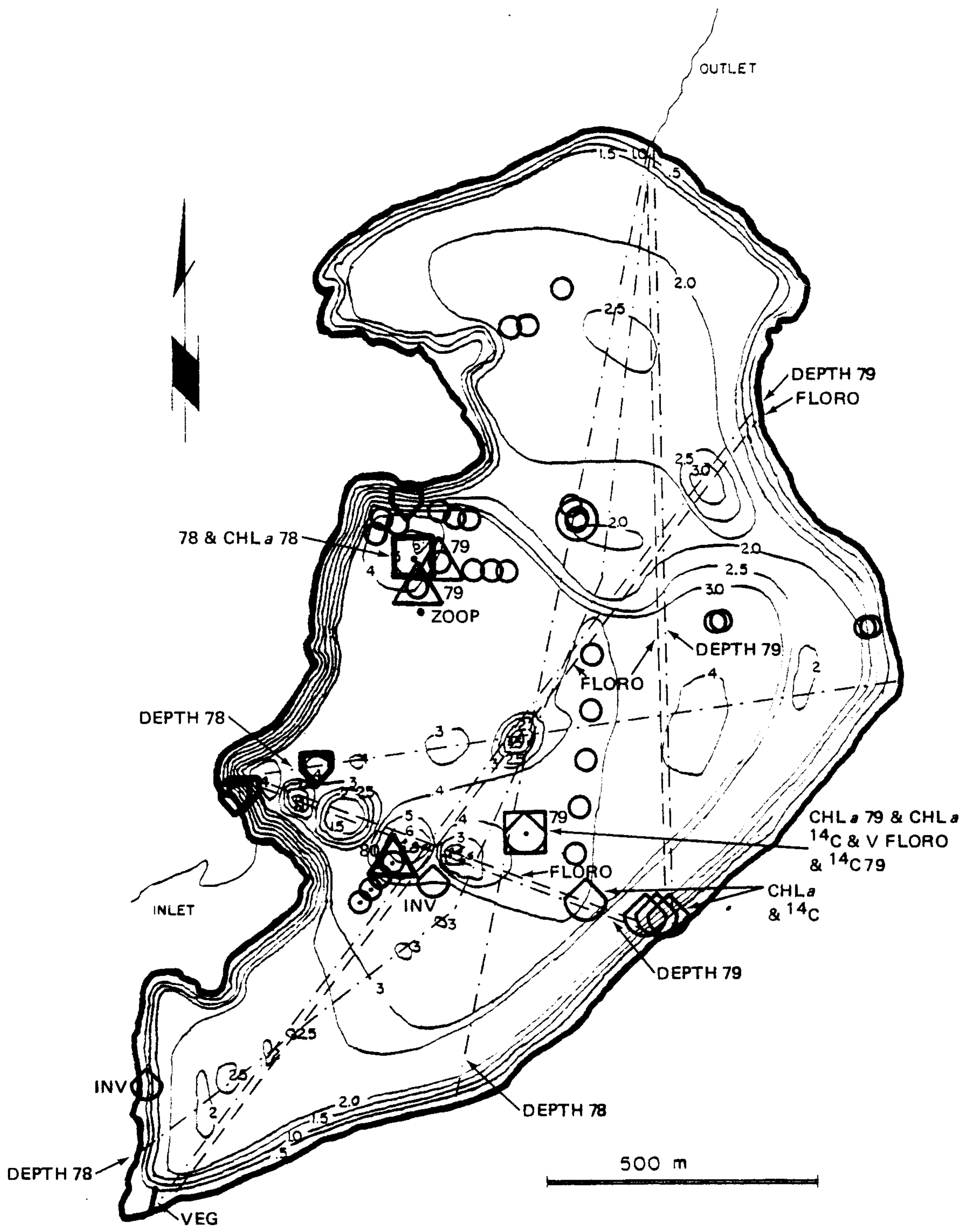


Fig. 34. Depth contours (m) plus stations and transects sampled in Lake C-1, Betty. (Table 2 gives key to symbols).

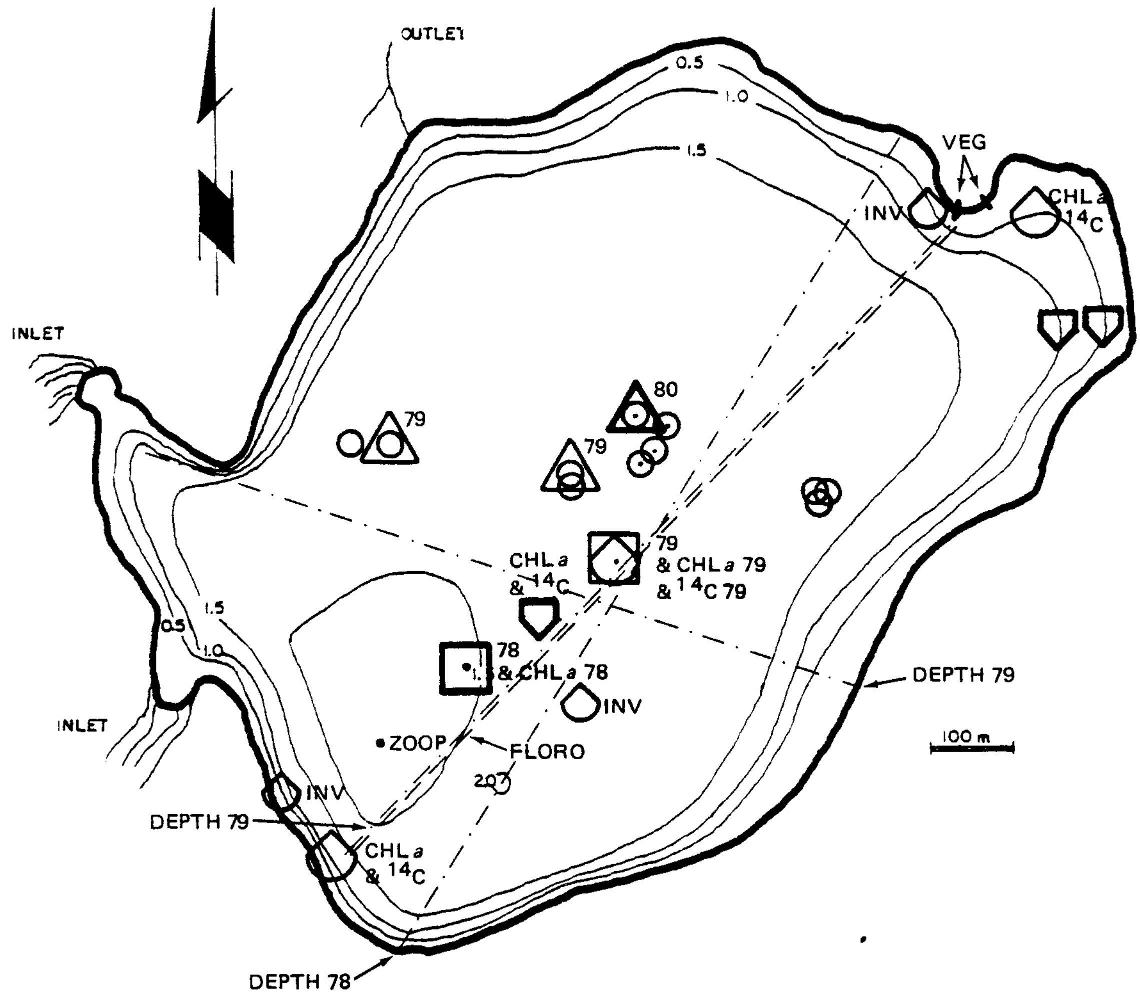


Fig. 35. Depth contours (m) plus stations and transects sampled in Lake C-2. (Table 2 gives key to symbols).

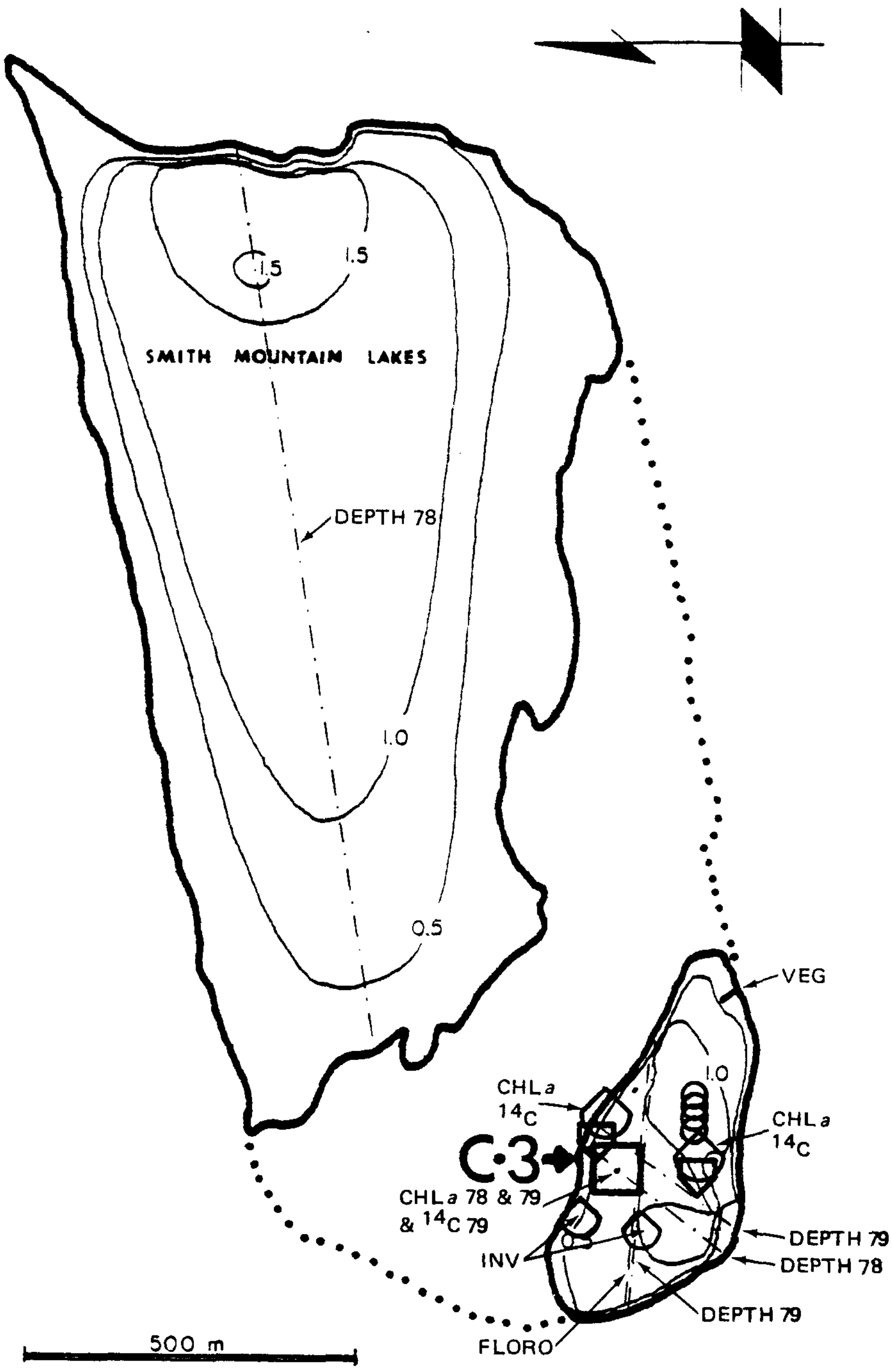


Fig. 36. Depth contours (m) plus stations and transects sampled in Lake C-3, Smith Mountain. (Table 2 gives key to symbols).

Lake Depths

The depth contours for 8 of the 9 study lakes were estimated from depth profiles acquired by summer fathometer transects. Pond B-3 was hand measured by rod as part of the vegetation transect. At least 2 fathometer transects were acquired on each lake (Figures 28-36). The transducer of a Lowrance LRG 1510 depth recording fathometer, with a transmission frequency of 192 kHz, was suspended between the floats of a float plane. The aircraft was taxied across the lakes at a constant speed to acquire lake depth profiles. Depth increments of 0.5 or 1 m were identified along each profile, were rescaled to lake shoreline maps, and were used to estimate isobaths on Figures 2-10 and 28-36.

Some inaccuracies resulted from this method. Sometimes the lake shoaled to such a degree that the aircraft could not reach shore to begin or end a transect. Identifying the start and stop points and maintaining a straight course for each transect was sometimes difficult. Some error was introduced when aircraft power settings were changed. Different power settings raise and lower the aircraft, because of both the hydrodynamics of the float pontoons and the aerodynamics of the wings. Some correction was made for these variables, but variations in surface winds versus power settings were infinite and only a finite number of calibrations were made. The fathometer record could be read to the nearest 5 cm with an accuracy of ± 5 cm: therefore, depth was ± 10 cm. The placement of these depth measurements within the lake basin was less exact than the depth accuracy. Two transects provided only 4 points from which to approximate a depth contour. The accuracy of the placement of those points depended on the accuracy of transect location and the accuracy of locating the point within the transect where a depth was acquired. For lakes B-1 and B-2 vertical aerial photographs were used to help me discern shoals and deeps for placement of depth contours. More transects were needed to adequately define the bathymetry of more complex lake morphology. For example, 4 and 6 transects were used on lakes B-1 and C-1, respectively. These lakes were difficult to contour, even with the larger number of transects acquired.

Lakes' surfaces are highest during break-up in May and June and lowest in September just before freeze over. All depth profiles were acquired in August of 1978 and 1979, long after spring break-up. Summer evaporation or rain can also change lake levels.

The method provided a quick, acceptable approximation of .5 m isobaths within each lake basin.

Ice Thickness and Related Measurements

Lake ice thickness data were required to interpret the depth contour zone at which ice cover contacted the bottom of a lake. Ice and snow thickness data have been collected from 3 to 4 locations in the Alaskan arctic by Bilello (1964) and Billello and Bates (1966, 1968, 1971, 1972 and 1975). These measurements illustrate the effects of climatic gradient across the Alaskan arctic and indicate annual variations in lake ice thicknesses; however, they were not sufficiently detailed nor were they placed well enough in time or space to be useful for SLAR image interpretation. Ice thicknesses were measured along the study transect during the same time period as SLAR image acquisition.

A ski equipped Cessna 185 or Beaver was used to land on and sample the 9 study lakes throughout the winter of 1978-79. A 20 cm auger or 10 cm Sipre corer (a 7.5 cm ice core is recovered) was used to drill holes through lake ice cover. Figure 37 illustrates the physical measurements taken at each hole. Snow depth was measured around the ice hole before it was compacted by drilling activity. All measurements were initiated at the snow/ice interface for ease of measurement. Free-board measured from the snow/ice interface to the water level within a hole should be subtracted from the water depth measurement for an accurate determination of actual water depth.

The percent snow cover on the surface of each lake was grossly extimated by an aerial observer at 500 feet above ground level.

Ice Cores

Eighteen ice cores were acquired using a Sipre Corer during this study. The 7.5 cm diameter ice cores were labeled and returned to the laboratory where they were kept frozen and analyzed within 1 to 3 days. The ice cores were inspected, measured, and photographed to document variations in quantity and morphology of gas bubbles within the ice.

Ice densities were approximated by a nondestructive method to preserve the core for photographs and further study. Each section was

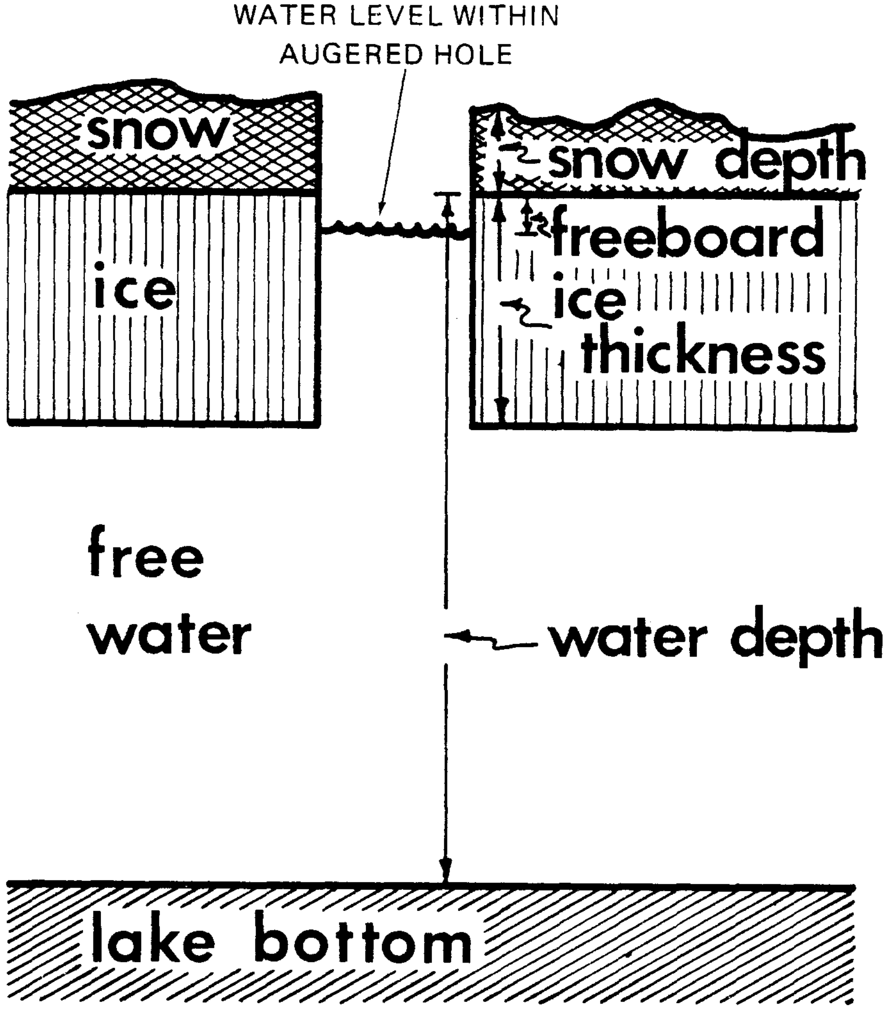


Fig. 37. Snow, ice, and water measurements.

immersed in water to obtain the core section volume. The volume measurement was less accurate than the weight measurement. Volumetric precision was ± 5 ml. The ice ranged in temperature from -5 to -20°C and cooled the water in which it was immersed during the measurement. The inaccuracies were toward lower volumes, thus higher densities. The core was removed and weighed immediately. The ratio of weight to volume provided a relative measure of density among core sections analyzed.

$$\text{Density (estimate)} = \frac{\text{Core section weight (gm)}}{\text{Core section volume (ml)}}$$

Specific conductance of 3 to 4 core sections (10 cm long) within a core were measured by destructive means. These core sections were removed from the whole core and were analyzed as soon as they were brought in from the field to prevent loss of salinity due to brine drainage. Core sections were melted, the water was heated to 25°C, and measured on an MC-1 Electrolytic Conductivity Measuring Set. Accuracy of measurement was approximately ± 3% of the values reported.

Temperature

Summer lake temperatures were measured by immersing a mercury thermometer in the water near mid-lake. The measurement precision was ± 0.2°C.

Temperature measurements were also acquired with the YSI dissolved oxygen meter during the April 1980 sampling. A measure of temperature was acquired simultaneously with dissolved oxygen at each depth within a lake profile. The meter was readable with reproducible precision to ± 0.25°C.

Suspended Sediment Load

Suspended sediment loads were sampled at the summer lakes' surfaces. One liter was returned to the Naval Arctic Research Laboratory (NARL) and filtered through a prewashed, oven and dessicant dried, and weighed HA millipore filter. The filter and sediment were redried and weighed upon return to the University of Alaska. This gravimetric method provided a precision of approximately 1 mg/ℓ. Results are reported to the nearest 0.1 mg/ℓ for relative differences in suspended sediment loads among lakes; 0.1 mg/ℓ is well within the limits of detection.

Light Attenuation

Light attenuation measurements were approximated by Secchi disc for the summer of 1978. A Secchi disc measurement was multiplied by a factor of 2 to obtain a gross approximation of photic depth or 1 percent incident light level (1% Io, Lind 1979).

A Li-cor Model L1-185 quantum/radiometer/photometer was used to profile light attenuation during the summer, 1979. A semilogarithmic plot of light versus depth was used to determine the vertical extinction coefficient (k) and the depth at which 1% Io occurred (Lind 1979). The 1% Io precision was approximately ± 0.5 m and was reported to the nearest 0.1 m to illustrate relative differences among study lakes rather than absolute values within a specific lake.

Specific Conductance

A summer specific conductance sample was collected from the surface water of each lake. The samples were analyzed on an MC-1 Electrolytic Conductivity Measuring Set. Each sample was brought to a temperature of 25°C before being analyzed to eliminate temperature compensation error. Accuracy is approximately ± 3% of the value. Results have been reported to the nearest 1 μ mhos/cm. Total dissolved matter in parts per million (ppm) was estimated from conductance by multiplying by an empirical factor of 0.65 (Lind 1979).

Winter specific conductance samples were collected from water that filled the ice holes and were representative of water found at the ice/water interface.

Nutrients

Summer nutrient samples were collected mid-lake at 0.5 m depth with a noncontaminating sampler. The samples were filtered through Gelman A/E glass fibre filters to remove particulates, placed in acid-washed polyethylene bottles with 4 drops of saturated mercuric chloride preservative solution, and frozen. Analyses for soluble NH_4, NO_2, NO_3, SiO_3, and PO_4 were carried out on a Technicon II Autoanalyzer system at the University of Alaska. Two to 4 replicate determinations were made for each sample and nutrient assayed.

Ammonia was assayed using a modified version of Head (1971) that substitutes a 30 minute time delay coil for the 60° heating bath, substitutes liquid phenal for crystalline phenol, and reduced the nitroprusside concentration. Analytical techniques provide precisions of approximately ± 0.1 microgram atoms per liter (μg at/ℓ).

Nitrate and nitrite methods were similar to those described in Strickland and Parsons (1968) but incorporated the reduction of nitrite using cadmium wire in conjunction with mercuric chloride. The nitrate technique provides precision of about ± 0.1 μg at/ℓ, and data are reported to the nearest 0.1 μg at/ℓ. Nitrite precision is ± 0.02 μg at/ℓ.

Silicate was determined by Strickland and Parsons (1968) methods reduced to accommodate a 20 sample per hour autoanalyzer rate. The precision of this method was about ± 0.25 μg at/ℓ.

The orthophosphate method was developed in the University of Alaska, Institute of Marine Science laboratory, and combines the methods of Murphy and Riley (1962), and Strickland and Parsons (1968). The precision was approximately ± 0.01 μg at/ℓ.

Under ice nutrient samples were acquired only from those 6 study lakes not yet frozen to the bottom in April 1980. The water collected was from within holes augered through the lake ice and best represented water at the ice/water interface.

pH, Alkalinity, and Dissolved Inorganic Carbon

Alkalinity and pH determinations were made with a Beckman pH meter and with methods and equations described in Strickland and Parsons (1968). The pH measurement precision was ± 0.02 pH units. The alkalinity measurement precision was approximately ± 0.1 mg/ℓ.

Dissolved inorganic carbon was calculated (Strickland and Parsons 1968) using the pH and alkalinities derived.

Dissolved Oxygen

During the winter of 1978-79, dissolved oxygen samples were taken from the water column between the ice/water and water/substrate interfaces. The samples were acquired with a water sampler through holes augered in the ice. The manganese sulfate solution and alkaline-iodine-azide reagent were added in the field. A great deal of effort was made to keep the samples from freezing before they were returned to NARL. Samples that froze sufficiently to be suspected of O_2 contamination were discarded. A modifier Winkler method was used to determine dissolved oxygen, with a precision of approximately ± 0.1 ml/ℓ.

During April 1980 some field dissolved oxygen measurements were made with a Model 57 YSI dissolved oxygen meter. The probe was kept well above freezing when it was carried between lake stations and was recalibrated at each station. The instrument maintained excellent calibration stability though subjected to -10 to -30°C air temperatures. Precision was ± 5 percent of the value.

Chlorophyll *a*

Chlorophyll *a* measurements were acquired during the summer of 1978 and replicated in 1979 with different methods. The field sampling and assay techniques differed for both water column and benthic samples and for the years during which they were acquired, 1978 and 1979. Water column samples were also acquired from beneath ice cover in April 1980 and were assayed in a manner similar to 1978 samples.

Summer 1978 water column profile samples were taken and analyzed by classical methods. Water was sampled at selected depths with a nonmetallic water sampler. The lake water was filtered through 47 mm Gelman A/E glass fibre filters (pore sizes 0.2 to 10 μm) in the presence of $MgCO_3$. The filters were air dried in the dark and frozen until the assay. They were assayed using 90 percent acetone extraction, standard spectrophotometric methods and equations in Strickland and Parsons (1968), and a Perkin Elmer Model 202 scanning spectrophotometer. This method provides results that are accurate to about ± 0.5 mg/m^3.

A Turner Designs Model 10005 R Fluorometer was used to measure *in situ* chlorophyll *a* profiles at a deep station and along surface transects during the summer, 1979. The fluorometer, water pump, and battery power supply were operated from the floatplane. Vertical profiles were taken by lowering a weighted suction hose to an appropriate depth, holding in position until the reading stabilized, and then lowering to another depth. The fluorometer was equipped with a Rustrak Recorder that was annotated with lake, date, depth, and sensitivity information. The surface transects were taken by lowering the weighted suction hose approximately 0.5 m while taxiing the floatplane across the lake in much the same manner as the fathometer measurements. In fact, some fluorometer and fathometer measurements were acquired simultaneously.

Fluorometer calibration was accomplished using acetone extraction of lake water and standard spectrophotometric methods (Strickland and

Parsons 1968). The precision of the calibration is on a sliding scale. Chlorophyll *a* values above 2.0 mg/m^3 are accurate to ± 1.0 mg/m^3 while values below 2.0 mg/m^3 are accurate to ± 0.5 mg/m^3. If relative differences rather than absolute values are considered, the fluorometer was sensitive down to ± .02 mg/m^3 chlorophyll *a*. The fluorometer values have been reported to the second decimal place to describe relative difference and should not be considered accurate below 1 mg/m^3. No calibration was conducted above 3 mg/m^3. The curve was extrapolated to obtain the highest values in this fairly linear region of the curve.

Summer 1978 benthic chlorophyll *a* samples were collected in 3.5 cm diameter core tubes. I collected some samples by diving and others by dropping a gravity corer. The plastic core tubes, which contained the sediments, were returned to NARL for analysis within several hours. The top 1/2 cm of hydrated sediment was siphoned off and filtered. The remainder of the sample preservation and assay was as described for the water column 1978 samples. The best precision to be expected from this benthic chlorophyll *a* method is ± 10 mg/m^2. The values are reported to the nearest full unit to preserve relative differences rather than absolute values.

Summer 1979 benthic samples for chlorophyll *a* were collected by a 15 cm square Ekman Dredge. The surface 1 cm of sediment was scooped from the samples and placed into a 1 ℓ bottle and was diluted to a volume of 500 ml. In the laboratory, 1 percent aliquots by volume were removed and filtered. The remainder of the sample preservation and assay was as described for the water column 1978 samples. These methods provided a gross approximation of chlorophyll *a*, with a detection sensitivity of ± 10 mg/m^2 and even less precision.

Stanley (1974) looked at chlorophyll *a* as a function of sediment depth in an arctic pond near Barrow. He found about half of the chlorophyll *a* was contained in the first 1 cm of sediment. The summer 1979 method used the top 1 cm of sediment from the Ekman sample. Although these methods provided only crude estimates of absolute quantities, each method was performed with as much standardization as possible to allow sample comparisons without concern for the degree of precision. The purpose of the study was to observe differences in chlorophyll *a* as a function of water depth and latitude rather than to determine precise values.

Under ice chlorophyll *a* samples were acquired only from those 6 study lakes not yet frozen to the bottom in April 1980. The water collected was from within holes augered through the lake ice and best represented water at the ice/water interface. The samples were handled and assayed as described for the summer chlorophyll *a* samples.

Primary Production

Water column and benthic samples for primary productivity measurements were acquired between 7 and 11 August 1979. The carbon-14 (^{14}C) method used was similar to that described by Vollenweider (1968). A bicarbonate solution containing a known quantity of ^{14}C was added to each of 2 light bottles and 1 dark bottle. Incubation was carried out *in situ* for 24 hours. The contents of each bottle were kept cool and in the dark until filtered through an HA 25 mm 0.45 μm millipore filter and then air dried. In the University of Alaska laboratory, the filters were fumed in the presence of concentrated HCl, extracted into a scintillation fluid, and counted with a Beckman LS100 liquid scintillation counter.

Water column samples were incubated in 125 ml bottles. After acid fuming, the extraction of ^{14}C from the filters could be performed by merely dissolving filter and residue in the scintillation fluid. The remainder of the assay was as described above. The precision of this method was approximately ± 15 percent of the values reported.

The benthic primary productivity samples were collected with a 15 cm square Ekman Dredge. The surface 1 cm of the dredge sample was scooped into a 1 ℓ bottle diluted to 500 ml volume and 1 percent aliquots were withdrawn, as for chlorophyll *a* samples. The aliquots were injected with ^{14}C and incubated in 24 ml vials alongside the water column samples for 24 hours. All other procedures were the same, except for ^{14}C extraction into the scintillation fluid. The sample could not be counted with any sediment in the scintillation fluid, because quench values were prohibitive. Therefore, each filter and its sediment were combusted in a Beckman Biological Material Oxydizer. Part of the CO_2 driven off was $^{14}CO_2$, which was trapped in a scintillation fluid containing phenethylamine. The CO_2 trapping efficiency was calibrated regularly and remained above 90 percent throughout. The sampling procedure, in addition to the error produced through sample handling for combustion and CO_2 trapping inefficiencies, gave less precise results than for water column measurements. The benthic primary productivities are recorded to the nearest 1 mg $C/m^2 \cdot day^1$ and have an approximate precision of ± 25 percent of the values reported.

Benthic Invertebrates

Benthic invertebrates were sampled by Ekman Dredge at 0.5 m, 1.0 m, 2.0 m and/or the deepest area found within each lake, during August 1979. Methods similar to those described in Lind (1979) were used for collecting and sorting macroinvertebrates. The samples were sieved through a #30 screen (600 μ opening in mesh) to separate the organisms from the sediment.

Only two replicate samples were taken at most stations and yet were qualitatively consistent in the type and relative numbers of organisms found. All the organism counts for each station depth were normalized to a sampling area of 0.05 m^2 or 2 Eckman Dredge samples before being reported in the results. Borror et al. (1976), Merritt and Cummins (1978), Pennak (1978), and Wiggins (1977) were used for taxonomic references.

Zooplankton

Zooplankton were sampled with a Wattman 200 μ mesh net with 100 μ apertures during August 1978. The cod end was 100 μ with 50 μ apertures. The mouth diameter was 12 cm. A single horizontal surface net tow was made near the middle of each lake. A net tow of 5 m was made at a retrieval rate of approximately 1 m per 3 sec., and care was taken to keep the mouth of the net open and completely below the water surface.

Vascular Emergent Vegetation

The vegetation transect locations were not randomly selected. The lakeshore area containing the most abundant emergent vegetation was selected by aerial survey. A transect was made across the widest portion of this area during early to mid-August 1979.

Water depth and plant density measurements and plant species and substrate identifications were made at 2 m intervals from shore on most lakes. However, for lakes A-1, A-2 and C-3, measurement intervals were determined by obvious changes in plant communities rather than at 2 m intervals. Water depths were measured by both methods in lakes A-1 and C-1. The 2 m interval method was found to be preferable, but both methods provided usable results.

Plant density was measured by counting the number of stems of each species present within a circle 10 cm^2 in area. If less than 1 plant occurred within the ring, but was present within the transect, the number of plants/stems within a 1 m length of transect were counted. The results were reported in 3 ranges of plant/stem density: < 1, 1-10, or > 10 stems per 10 cm^2. Hultén (1974) was used as the reference for plant identification.

The substrate identified, whether organic or inorganic, was the first matter encountered beneath the water. It was often a mat of dead and/or live vegetation. No attempt was made to determine the type of substrate below this mat, which in some places was 30 cm or more thick.

Fish

Only lakes deeper than maximum winter ice thicknesses ($\approx$ 2 m) or that had an inlet and/or outlet through which fish could enter during the ice-free period were sampled for fish.

Lake C-1 was sampled by the Alaska Department of Fish and Game (1977) before this project began. The lakes sampled for fish during this project are: A-2, B-1, and B-2. During the summers of 1978 and 1979 the 3 study lakes were sampled with minnow traps baited with sterilized salmon eggs or canned turkey. They were also sampled with 38 m long experimental gill nets, set for a minimum of 24 hours. Both sinking and floating nets were used. Fish caught were weighed and measured by fork length, and scales were collected for aging.

RESULTS AND DISCUSSION

Study Lakes Descriptions

Lake A-1

Lake A-1, Imikpuk Lake, is the most northern of the study lakes and is actually the most northern fresh-water lake on the North American Continent. Lake A-1 is immediately adjacent to the Naval Arctic Research Laboratory (NARL). Because of its close proximity to NARL and its importance as a fresh-water supply for the laboratory, A-1 has been the object of many studies (e.g. Brewer 1958).

Lake A-1 has been subjected to both human and natural contamination, and its shore is encircled with roads and pipelines. A gasoline spill estimated at 200,000 liters occurred adjacent to the northern shore in August 1976. A fraction of that spill seeped into the northern end of A-1, and has been the subject of a study of hydrocarbon effects on microbial activities (Horowitz and Atlas 1977, Horowitz et al. 1978). Lake A-1 is separated from the ocean by a gravel beach approximately 120 m wide. The lake suffered some saltwater contamination when ocean waves breached the beach during storms in October of both 1954 and 1963.

Lake A-1 is the deepest of the "A" lakes, with a maximum recorded depth of 3.1 m (Figure 28). It has no well-defined inlet but has a gate controlled outlet into North Salt Lagoon from the marshy area on the northeastern shore (Figure 11). The bottom substrate consists of gravel near the shore and grades into soft sediments in the deep areas. Although this lake was easily accessible, had data from previous studies, and was one of few fitting the $\geqslant$ 3 m depth category, its immediate proximity to human and marine disturbance make it less representative than desired as some anomalous data support in hindsight.

Lake A-2

Lake A-2, Ikroavik Lake, is approximately 10 km south of Lake A-1 (Figure 11). The largest of the 9 lakes studied, Lake A-2 has an area of 514 ha, and is farther from the ocean (approximately 6 km) than are A-1 or A-3. Ikroavik was the object of the International Biological Program Tundra Biome study Hobbie (1980) and Carson and Hussey (1960, 1962) lake orientation research.

The maximum depth of A-2 is 2.1 m in the southern end (Figure 29). Most of the middle of the basin is 2 m deep. The inlets are fairly insignificant, but an outlet exists at the southeastern end. This outlet becomes Avak Creek, which drains into Iko Bay. Since A-2 is the headwaters of this drainage, it is the terminus of summer fish migrations. Ninespine sticklebacks, *Pungitius pungitius,* and least cisco, *Coregonus sardinella,* have been caught in A-2. Wave-cut peat is evident along the shore, but soft sediment is the predominant substrate.

Lake A-3

Lake A-3, West Twin Lake, is the shallowest of the Northern Coastal Plain study lakes with a maximum recorded depth of 1.2 m (Figure 30), and has a surface area approximately twice that of A-1 and one quarter that of A-2.

The lake bottom is uniform, consisting of smooth soft sediment, with some peat-covered areas. No defined inlets or outlets exist. The northern end is only 800 m from saltwater in Elson Lagoon. This lake has not been sampled for fish, because it is too shallow to support an overwinter fish population.

Lake B-1

Lake B-1 is the deepest of the 9 study lakes. It has 2 deep areas, as shown in Figure 31. The southwestern half of the lake has the deepest basin, with a maximum recorded depth of 11.5 m, and the northeastern half has a smaller basin, with depths to approximately 8 m. Lake B-1 may have been 2 separate deep-basined lakes that merged some time in the past.

Lake B-1 is 217 ha in surface area, the largest of the "B" lakes, but does not have the usual axis orientation. Each of the 2 basin deeps had the expected orientation, but their apparent merging caused a changed orientation for the lake surface.

The bottom substrate is clean white sand extending from shore to approximately 1 m water depth. Soft sediments with some detritus cover the deep areas. Ninespine sticklebacks and cisco have been caught in this deep lake. Lake B-1 has no predominate inlets but does have an outlet on the northern shore. This is the headwaters of the Okpiksak River, which joins the Meade River.

Lake B-2

Lake B-2 is the mid-depth lake in this mid-transect study area. The lake shore has receeded leaving wet sedge meadow. The present lake surface area is 106 ha or approximately half the area of B-1.

The deepest area recorded (1.9 m) was slightly south of mid-lake (Figure 32). The lakeshore was difficult to map or even to identify on the ground. The drained lakebed is a marshy continuum that changes slowly into the emergent vegetation on the lake shelf. The shoals of the lake shelf extend for approximately 200 m into the lake, where the shelf breaks sharply at 0.5 m. Emergent lake vegetation extends across about 70 m of this shelf. The remainder of the shelf is firmly packed sand. Beyond the shelf break, soft sediments predominate.

Lake B-2 has no inlets and drains through an inconspicuous marshy outlet on the northwestern shore. The outlet drains into the Usuktuk River and finally into the Meade River. The ninespine stickleback has been found in B-2.

Pond B-3

Pond B-3 is the smallest and shallowest of the basins studied. It is only 0.45 m deep (Figure 33). Approximately 30 m of marsh separate the pond from an adjacent lake. Pond B-3 is the darkened one of four small dots (ponds) just west of the larger lake in Figure 12. It is 160 m long and 90 m wide, and although difficult to deliniate, its surface area is approximately 1 ha.

The pond shore is fairly abrupt. The bottom substrate is smooth and flat with firm fine sand and a high concentration of organic materials. The pond has sparse but continuous emergent vegetation. No fish were seen, but the potential exists for small fish, such as the ninespine stickleback, to migrate from the deep lake through the marshy area during periods of high water. Fish could not overwinter since the pond freezes to the bottom.

Lake C-1

Lake C-1, Betty Lake, is the deepest and largest of the Foothill study lakes (Figure 13). It was used as a winter oil exploration logistics base during the winter of 1978-79. The frozen lake surface was used as a runway for large Hercules aircraft that transported materials and supplies to the base.

The lake basin morphology is complex, as may be seen from the estimated depth contours shown in Figure 34. The greatest depth (6.8 m) was recorded southwest of the lake center. Another almost equally deep hole was found near the western shore in the upper two-thirds of Betty Lake. Two major basins are within the lake. The northern basin has a uniform shallow bottom not exceeding approximately 3 m in depth. The central basin has an irregular bottom, with knobs to within 1.5 m of the surface and holes from 4 to 7 m deep.

The major inlet is on the southwestern shore. The outlet is from the northern shore. It drains into the Etivluk River, which feeds the Colville River. Lake trout *Salvelinus namaycush*, arctic grayling *Thymallus arcticus*, and broad whitefish *Coregonus nasus* have been caught in this lake. The substrate is predominately gravel and sediment near shore and fine sediment with detritus in mid-basin. Little vegetation extends into the lake except from the southern marshy shore.

Lake C-2

Lake C-2 is about 10 km west of C-1 (Figure 13). It is bordered by marsh to the west and has poorly defined inlets and outlets; however, all lake drainage occurs through the marsh on the northwestern lakeshore.

The southern and western shelf is narrow, with a fairly abrupt break near shore (Figure 35). The eastern side has a wider shelf that has almost no break. The shelf is a mixture of peat, sand, gravel, and fine sediment. The flat interior basin is covered with mud. C-2 is almost 1.3 km long, more than 0.9 km wide, and has a maximum depth of 2 m. Little vascular vegetation grows beyond the lakeshore.

Lake C-3

Lake C-3 is part of the Smith Mountain Lake complex, 30 km north of lakes C-1 and C-2. The USGS chart used for Figure 13 originally showed the large eastern basin as a single lake. This basin has drained sufficiently to create 2 lakes separated by a marsh more than 200 m wide (Figure 36). Lake C-3 is 250 m wide, less than 600 m long, has a surface area of only 10 ha, and a maximum recorded depth of 1.1 m. The bottom increases in depth more rapidly on the southern bluff-lined shore than elsewhere. No significant inlet or outlet exists. It has several patches of emergent vegetation along the southern and eastern shores. The substrate is soft mud. The southern shore has some 1 to 2 m bluffs, while the northern shore is flat and marshy. No fish collections were attempted, because Lake C-3 is too shallow to support an overwinter fish population.

Lake Depth

All limnological constituents were sampled at preselected and standardized water depths to enable water depth effects to be studied for each aquatic constituent. In this way the water depth was maintained as a control, as much as possible, rather than as a variable.

Lake basin morphology changes from study areas A to B and from B to C. In the Lake Study Area A, on the northern end of the transect, maximum lake depths seldom exceed 2.5 m. Lake A-1, at 3.1 m depth, is the exception rather than the rule. Lakes A-2 and A-3 are typical examples of the thaw lakes prevalent within Area "A". The lake bottoms are smooth and flat with no mid-basin irregularities such as deep holes or knobs. This shallow basin morphology is typical for the first 90 km inland from Point Barrow within the transect. Area "B", within the Mid-Coastal Plain, has many lakes that exceed a 3 m maximum depth. These lakes have broad shallow shelves, with north/south oriented mid-basin deeps. Lake B-1 is typical of the area. Area "B" is within a 50 km mid-section of the transect that has high lake density and many deep lakes. Lake density decreases abruptly at the end of this 50 km section as the foothills begin. The remainder of the transect, traversing the foothills into the Brooks Range, has few lakes, each of which is specific in basin shape and depth depending on the geomorphology of the surrounding terrain. Since lakes in Area "C" are a product of the geographic setting, they have no typical depth, but are often deeper than the 1-3 m seen in most of the Northern Coastal Plain lakes.

Although study lakes were choosen to fit into a gross but fixed set of depth categories (> 3 m, ≈ 2 m, and ≤ 1 m), the bathymetry and morphology of lake basins varied between the different study areas along the transect. The bathymetry of the medium-deep lakes (2 m) was most similar, typifying thaw lakes. Some variations exist in the $\leqslant 1$ m shallow basins. Lakes C-3 and B-3 formed as the result of partial draining of larger, deeper adjacent lake basins, and A-3 is a large, shallow thaw lake basin. The bathymetry of the deep lakes (lakes A-1, B-1, and C-1) varies the most. Lake comparisons made within or among the 3 categories must be carefully considered relative to the category variations described above; however, lake sampling went beyond these categories because constituents were sampled at discrete and specific depths (i.e. 0.5 m, 1.0 m, 2.0 m, and maximum attainable depth) within each lake for a more quantitative basis for comparison within the variety of lakes considered.

Variations in Ice Thickness

A number of climatic and physical factors control ice thicknesses on Alaskan arctic lakes. The history of ice formation each year is unique in that temperatures, winds, snow cover, time of and conditions during freeze over are infinitely variable. Some of the relationships between physical factors and ice thickness were evident in the data collected. The objective was to collect sufficient ice thickness data at specific lakes throughout a winter to predict approximate thicknesses at any lake within the transect at any time. Factors other than time and latitude that affected ice thickness significantly, such as snow depth, should be recognized as variables capable of producing error in a time/latitude model.

Snow Depth

Ice thicknesses as a function of snow depth have been illustrated for 2 different time periods during winter ice growth. Figure 38 depicts the conditions along the Transect, during November 1978, less than 2 months after initial freeze over. The number of data points for this analysis were few, but the trend shown is logical. The deeper 2 lakes (nos. 1 and 2) within each study area were measured for ice thickness and snow depth at several stations between 20 and 24 November. The deepest lakes A-1, B-1, and C-1 are shown as circles with center dots. The mid-depth lakes A-2, B-2, and C-2 are shown with pluses in the center of circles. All of the points shown for each study area are used in a least squares fit to produce the linear regressions shown in Figure 38. To establish how well the data used fit each linear regression, a correlation coefficient, r, was calculated. At $r = 0$ no fit exists, while at $r = \pm 1$, the fit is perfect. Correlation coefficients for the least squares fit for points in areas "A" and "B" were reasonably good with $r = -0.78$ and -0.72, respectively. The spread of the 7 measurement points in Area "C" provided a poor correlation coefficient ($r = -0.44$) for acceptance of the linear regression.

The linear regression lines in Figure 38 depict 2 trends. The ice thickness at the X-intercept represents the ice thickness with no snow cover. Areas "A", "B", and "C" show ice thicknesses of 85 cm, 71 cm, and 61 cm, respectively. The northern lakes appear to be freezing faster than the southern lakes. The slope of each line represents the change in ice thickness with changes in snow depth. Every 1 cm of snow

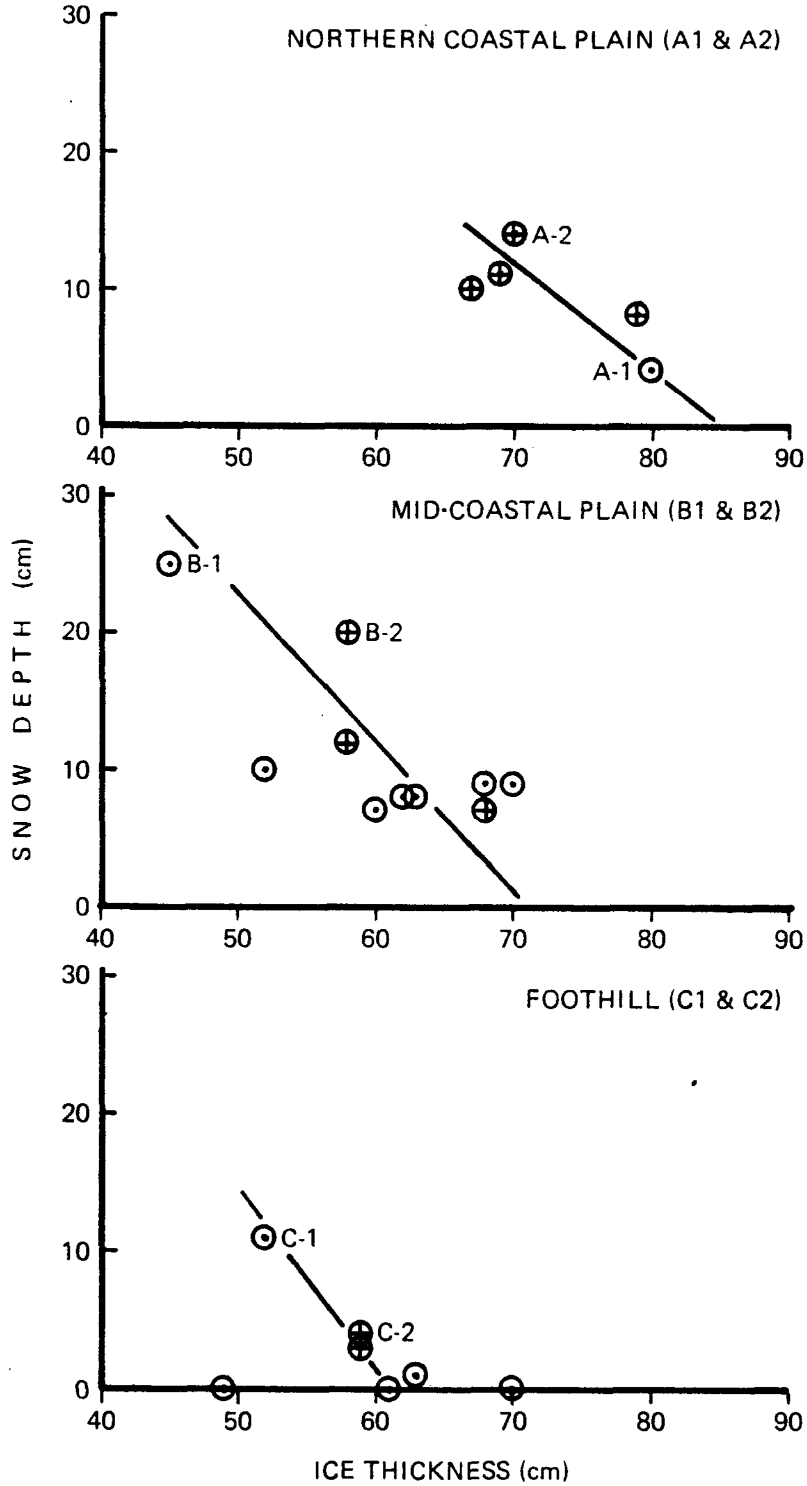


Fig. 38. Early winter (20-24 November 1978) ice thickness as a function of snow depth on study lakes.

depth decreases ice thickness by 1.25 cm, 0.95 cm, and 0.75 cm for areas "A", "B", and "C" respectively. Snow cover has a greater effect on ice growth at the northern end of the transect than the southern end, as the same insulation is more effective with increased thermal gradient. The snow insulates against colder air temperatures and more persistent winds in area "A" than in "B" or "C".

A similar set of data is shown for spring of the same year in Figure 39. Snow in place over the ice cover had had more time to insulate the ice cover. Each snow and ice measurement was taken at a specific place and time. No history of snow depths at a sampling station was known or taken into account in this analysis. The "A" and "B" areas were sampled during mid-March while the Foothill lakes in Area "C" were not sampled until 8 April; therefore, ice at Area "C" had an additional 3 weeks to grow. The correlation coefficients for linear regression are r = -0.90, -0.72, and -0.96 for areas "A", "B", and "C", respectively. The correlation coefficients are much bigger in late winter (Figure 39) than in early winter (Figure 38). Snow insulation had had 6 months rather than only 2 months to affect a larger difference in ice growth and a stronger correlation with local climatic and snow cover conditions. Figure 39 linear regressions show that each 1 cm of snow depth decreases ice thickness by 2.31 cm, 2.06 cm, and 1.65 cm for areas "A", "B", and "C", respectively. The Northern Coastal Plain "A" lakes appear to be affected most by the insulating properties of a snow cover. The March and April snow cover was shown to have affected ice thickness twice as much as the November snow cover. For example,

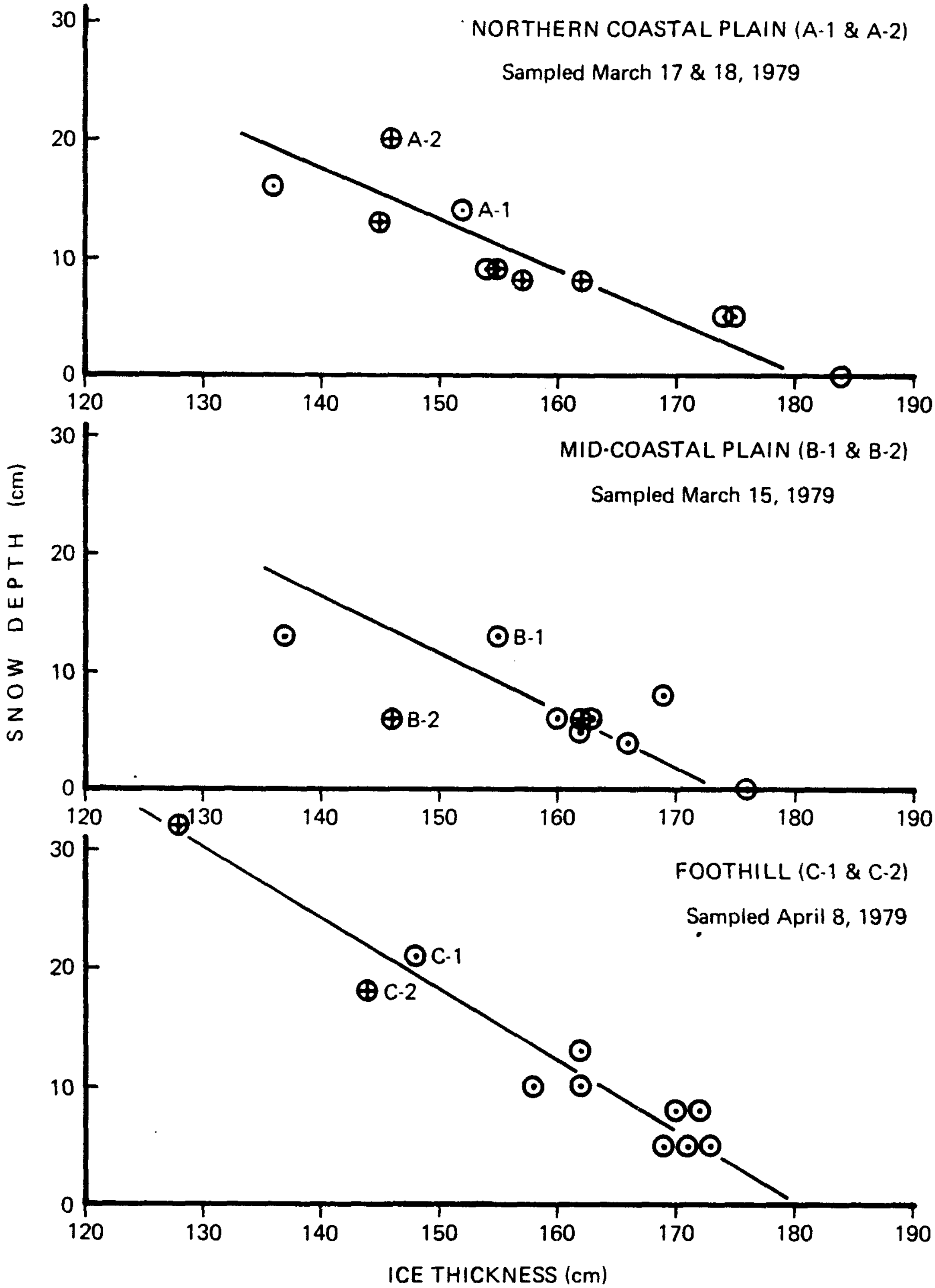


Fig. 39. Spring (March and April 1979) ice thickness as a function of snow depth on study lakes.

each 1 cm of snow reduced Area "B" lake ice thickness by 0.92 cm in November and by 2.06 cm in March.

Over-ice

Another phenomenon that may cause variations in ice thickness is the flooding of ice covered lakes with water that upwells through cracks in the ice. After flooding the surface, the water begins to freeze both at the ice/water and water/air interfaces, thus trapping and incorporating all dissolved and suspended solids and gases in the ice matrix. This forms a milky or discolored ice which I will call over-ice. Over-ice has been observed on all study lakes except B-3. Over-ice was observed soon after lake freeze over in October 1978. Most of the Alaskan arctic lake surfaces had frozen by 29 September 1978, but no snow had fallen by 11 October. The ice thickness was approximately 13 cm on the Northern Coastal Plain lakes by 11 October. The dark surfaces of the thin ice lacking snow cover provided a background with good contrast for observing the milky-white bands of over-ice that crossed most lakes. As a gross estimate, from 0 to 30 percent of a lake may have had over-ice. Over-ice 24 cm thick was recorded on Lake C-1 which was a significant part of the November 1978 total ice sheet thickness of 63 cm.

Over-ice was observed to occur early in the freezing season which coincided with potentially large fluctuations in climatic conditions and temperature. Large temperature variations probably cause over-ice to form. As ice continues to contract upon cooling, cracks form. Water then fills the cracks and freezes, forming a continuous ice cover. When warmed, the ice expands, pressing against the shore with nowhere to go. Undulations, formed in the compressing ice sheet, may be forced below the lake surface. Small cracks in the ice permit the ice surface to be flooded and over-ice is formed. Over-ice formations observed were primarily linear and often extended across nearly an entire lake. Less frequently, circular or oval over-ice features were observed.

Ice Growth near Lake Bottom

Brewer (1958) stated that bottom sediments, bacterial action and solar radiation are sources of winter water column heat. If restricted to water confined between close ice and lake bottom surfaces, these heat sources can slow ice growth just before it contacts the lake bottom. Insufficient data were collected to make an adequate analysis of this factor, but logic and experience indicate that ice growth slows as the ice thickness approaches total water depth.

Ice Cores

Ice morphology is a function of the history of ice formation. Conditions of freeze over, snow cover, over-ice and those of temperature, dissolved solids, and dissolved gases in the water column below the ice all interact in ice formation history. Twelve sipre cores were acquired during the winter of 1978-79, 2 during April 1980, and 4 during April 1981 to help ascertain differences in ice morphology for the lakes being studied. Any surface cover characteristic that increases or decreases the insulation between the cold arctic air mass and the water beneath the ice cover can affect ice thickness. The thickness of ice itself affects its rate of growth. Variations in the quantity and size of bubbles in the ice change the insulating quality of ice and subsequently its thickness. Observations of ice core morphology provided information on the bubbles and other nongaseous impurities within the ice. Ice cores from lakes A-1, A-3, B-1, B-2, C-1, C-2, and from deep areas in Teshekpuk Lake, 100 km east of the study transect (Figure 1), were photographed to compare gas bubble size and number. Cores from April 1979 ice cover on lakes A-1, B-1, and C-1 were sectioned and analyzed for changes in ice density due to gas bubble content and for changes in specific conductance with core depth.

Specific conductance, for the most part, increased with increasing depth within the ice cores; however, cores often had a high specific conductance at the surface. Figure 40 illustrates specific conductances (μmhos) relative to depths at which measurements were made within ice cores taken from lakes A-1, B-1 and C-1. The specific conductance of water below the ice is shown for each lake and for the snow above Lake C-1. Specific conductance of the ice is least in the top one-third of the ice cores, and increases slowly with depth.

As the specific conductance of the lake water is increased by salt rejection from the thickening ice cover, the ice becomes increasingly contaminated by the concentrated dissolved solids. A large increase at the ice/water interface (C-1) may have resulted from lake water retained between forming ice crystal platlets or from some contamination

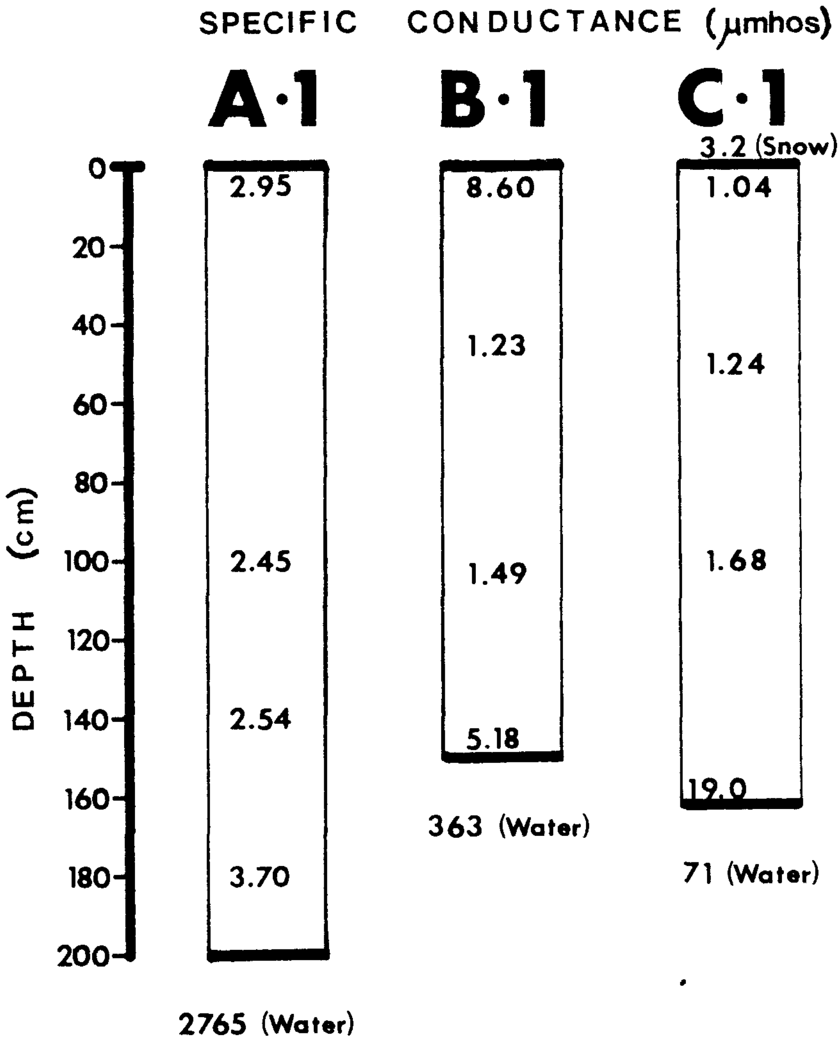


Fig. 40. Specific conductances within ice-cores from lakes A-1, B-1, and C-1, sampled April 1979.

of the bottom core section as water entered the hole during sampling. The higher surface values for all cores is the result of conditions during freeze over. Rapid freezing of wind drifted ice crystals can trap interstitial water. Surface contamination such as over-ice can also add to ice surface salt contamination.

A description of ice densities and gas bubbles found in the ice cores helps characterize the ice covering the lakes. Interstitial gas bubbles is important to the variation in SLAR return signal strength from imaged lakes. Densities of ice core sections were estimated as described in the methods section. The estimates may be slightly higher than actual densities, but they are adequate for relative measures of bubble content between sections of ice cores. Pounder (1965) gave the density of pure ice at 0°C as 0.9168 g/cm^3, and stated that density of ice containing air bubbles may easily be as low as 0.86 g/cm^3. Ice core densities estimated during this study ranged from 0.941 g/ml to 0.867 g/ml. The maximum density in the 6 cores analyzed occurred within the top 50 cm of the cores and averaged 0.929 g/ml. Most ice cores had few if any bubbles near the surface unless over-ice was present. The number of bubbles began to increase at 10 to 40 cm ice depth, with a corresponding decrease in ice core density. Four ice cores acquired from lakes A-1, B-1, B-2, and C-1 in April 1979 reached an average minimum density of 0.89 g/ml within 5 to 40 cm of the bottom of the 150 to 200 cm thick ice sheets. Within any discrete ice sheet, gas bubble content tended to increase with depth within an ice sheet.

Spherical and columnar gas bubbles coexisted in the ice sheet. The spherical bubbles ranged from < 0.1 mm to 1 cm in diameter. These spherical or inverted tear drop shaped bubbles appearred at any depth within the ice and were the only type found in over-ice. Columnar bubbles were from a few millimeters to 12 cm or more in length. Diameters ranged from < 1 to 5 mm. The elongate bubbles often occurred in obvious bands, where gases had come out of solution for awhile, stopped or slowed substantially for awhile, and then restarted to form another band. In some cores, the bubbles were so dense that the banding was camouflaged, while in others the bands of bubbles were analogous to tree rings only much wider (1 to 20 cm). Bubble orientation was vertical.

All gases must come out of solution and be incorporated into the ice sheet in lake areas that freeze to the bottom. As lake depths increase over freezing depth (> 2 m) some of the gas remains in solution, and gas bubbles in the ice sheet become fewer. The ice cores taken from lake areas ⩾ 4 m deep had very few to no columnar gas bubbles. The numbers of gas bubbles incorporated in ice decrease with increasing lake depth from thousands per core in lakes ⩽ 2 m to few or none per core in lake areas > 4 m deep.

The mixing of shallow lakes maintains summer dissolved gases at near saturation levels; however, winter freeze over comes on rapidly, cooling the waters to near freezing temperature, which may leave the water slightly below saturation. Solubility is increased by from 2 to 3 percent for every 1°C of cooling. Freeze over stops the exchange of gases between the atmosphere and water column, and continued ice accretion concentrates the gases into limited space below the ice. After the ice cover is in place, the water column may be warmed by biological activity, heat from bottom sediments, but primarily by solar radiation (Brewer 1958). A slight warming of the water or the continued concentration of gases being excluded from the ice cover finally cause the gases to saturate and come out of solution, forming bubbles on the under surface of the ice. As long as environmental conditions remain fairly constant, the gases continue to come out of solution, forming continuous elongate (columns) bubbles in the growing ice cover.

Ice Thickness Changes with Time and Climatic Gradient

Study Areas A, B, and C. The ice thicknesses sampled throughout the winter 1978-79 were measured for the most part on the no. 1 ($\geqslant$ 3 m) and no. 2 ($\approx$ 2 m) study lakes. Figures 41, 42, and 43 have these measurements plotted for the dates at which they were acquired in study areas A, B, and C, respectively. When 2 or more ice thickness measurements were taken on one date, the measurements were averaged and the mean value denoted by a horizontal bar. The mean values have been connected to form the curve depicted for each study area. The curves were drawn utilizing major climatic events from air temperature data (Braden 1979) to help establish the curve and best represent ice thickness throughout the entire season. None of the ice thickness values plotted have been corrected for variations in snow depth or over-ice conditions specific to individual sampling locations; rather, enough measurements

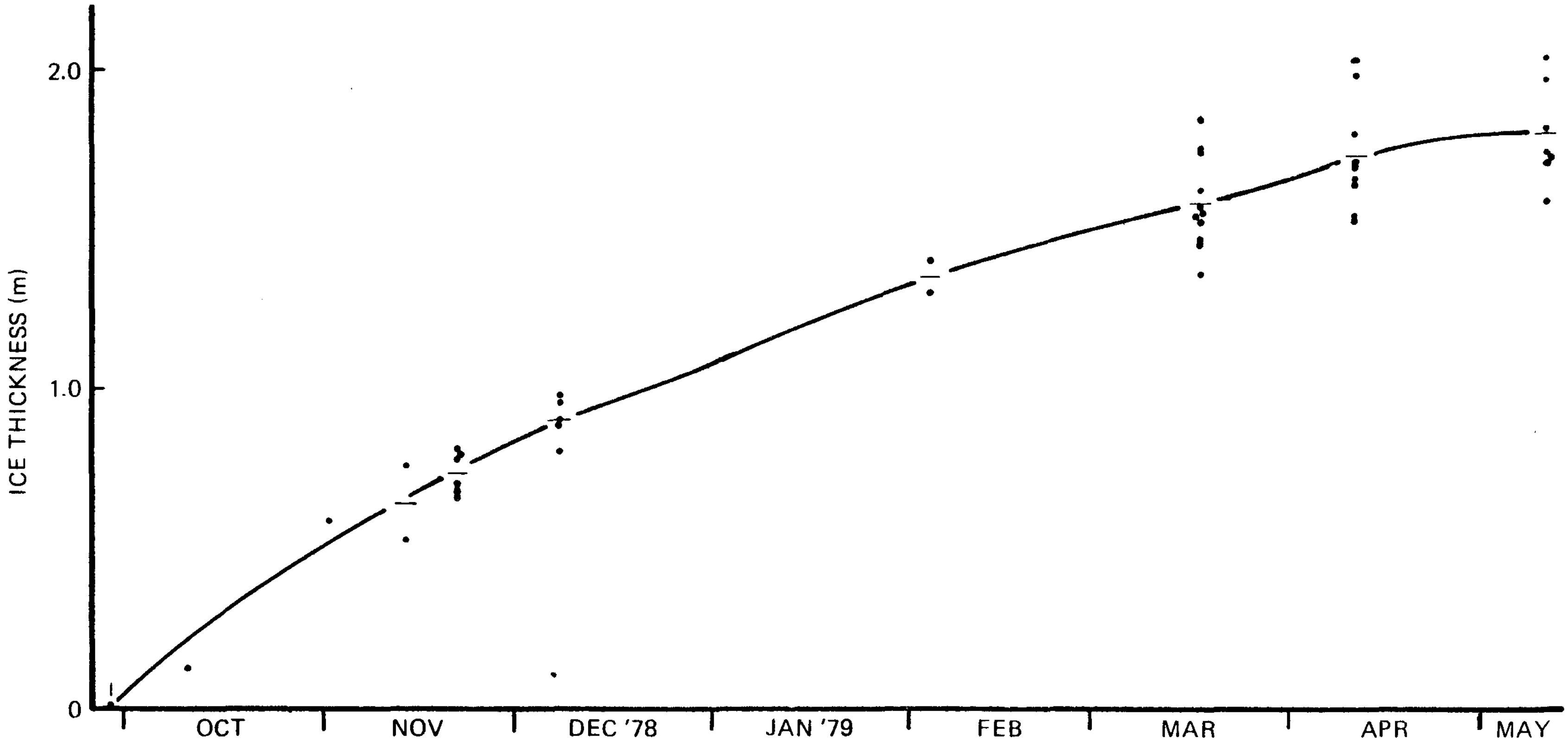


Fig. 41. Ice thicknesses on Northern Coastal Plain lakes A-1 and A-2 throughout 1978-79 winter growth.

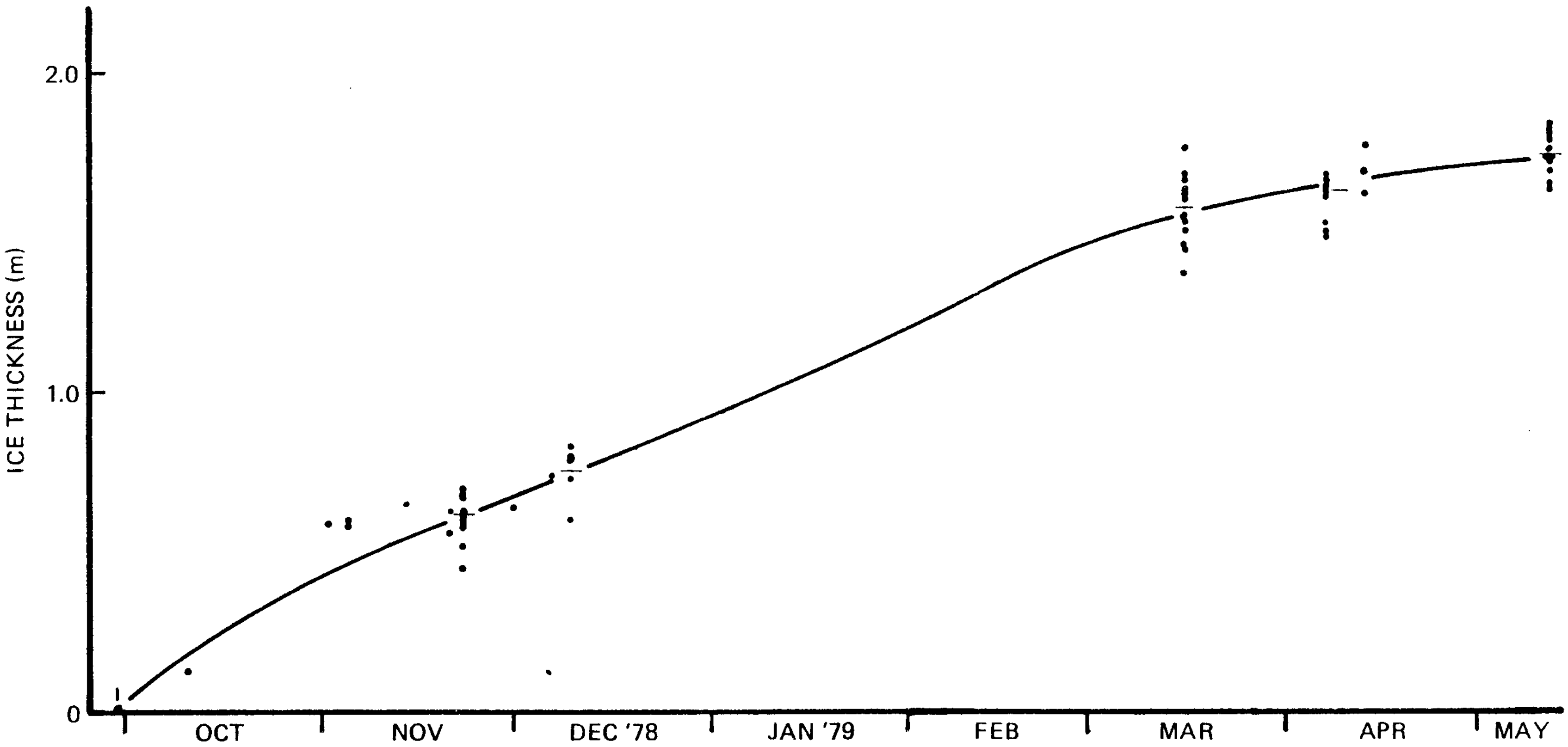


Fig. 42. Ice thicknesses on Mid-Coastal Plain lakes B-1 and B-2 throughout 1978-79 winter growth.

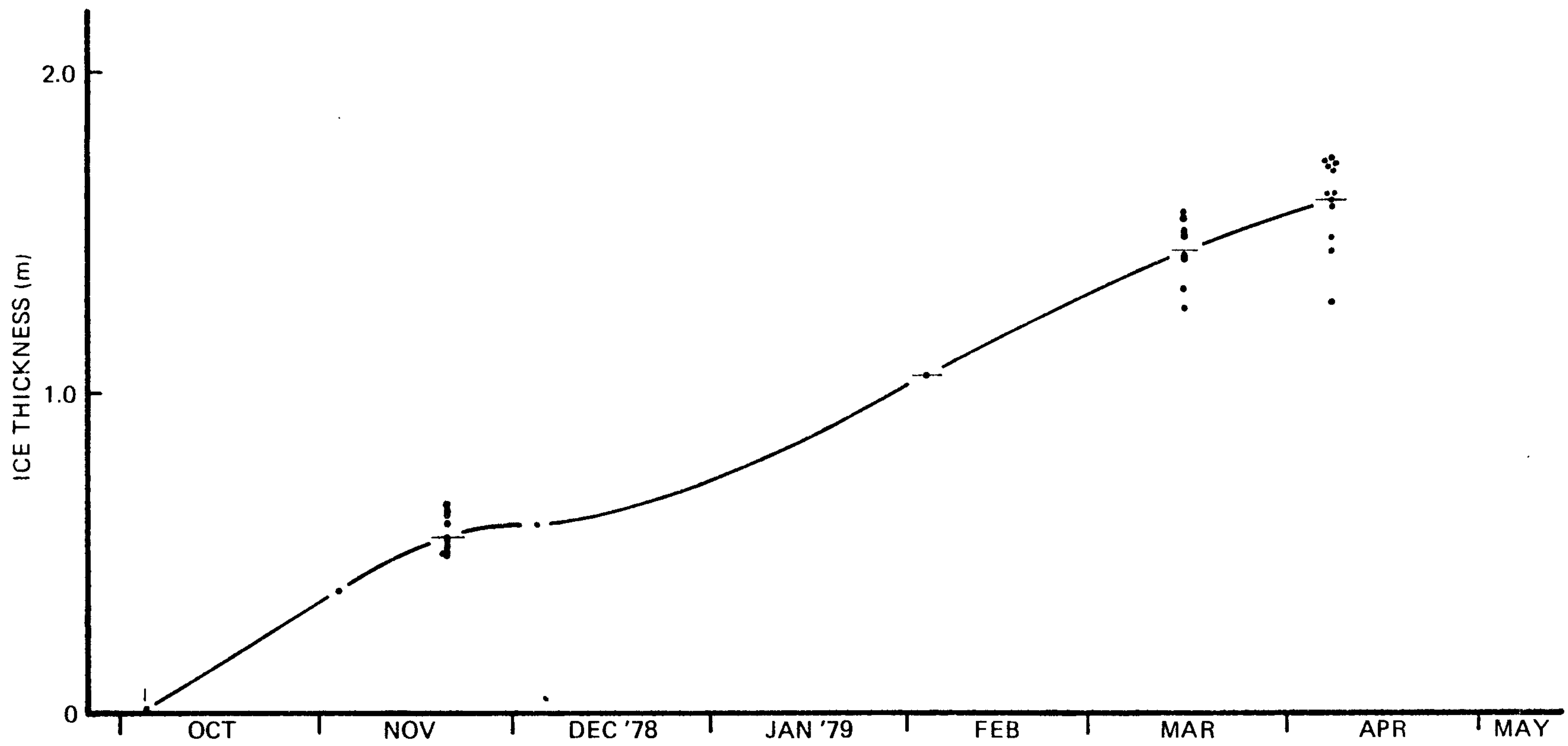


Fig. 43. Ice thicknesses on Foothill lakes C-1, C-2, and C-3 throughout 1978-79 winter growth.

were made in an attempt to sample the maximum variability that existed. The measurements plotted provide insight into the range of ice thicknesses found and the number of measurements used to obtain the mean ice thickness. Freeze over in 1978 was later than the usual mid-September occurrence (Brewer 1958) with coastal plain lakes freezing over in late September and foothill lakes in early October.

Ice thicknesses on the Northern Coastal Plain Transect lakes (Figure 41) increased fairly steadily to 180 cm in May. A total of 46 ice thickness measurements from lakes A-1 and A-2 ice covers were used to define this curve. September 29, 1978 was the approximate date for freeze over, and ice accretion was continuing 8.5 months later when the final measurement survey was conducted in mid-May 1979.

The Mid-Coastal Plain Transect lakes' average ice thickness curve (Figure 42) was approximated from a total of 58 ice thickness measurements acquired from lakes B-1 and B-2 during the winter 1978-79. Freeze over occurred on about 30 September 1978, and the average ice thickness had leveled out at about 166 cm by the last survey in mid-May. Ice thicknesses increased rapidly until mid-November, when the rate of growth was slowed through late November and December (Figure 42). Temperature charts (Braden 1979) show an increase in Alaskan arctic air temperatures of approximately 10°C above the norm for a month beginning in November and continuing into December. This temperature increase correlates well with the decrease in the rate of ice growth.

The Foothill Transect lakes' average ice thickness curve (Figure 43) was estimated from a total of 32 ice thickness measurements acquired from lakes C-1, C-2, and C-3 during the winter 1978-79. Freeze over occurred on about 5 October 1978. The average ice thickness was still increasing at 160 cm when the last Foothill lake ice survey was made on 8 April 1979; however, on the following visit, 13 May 1979, the surface of "C" lakes ice cover had melted sufficiently so that the ski equipped Beaver could not land because of danger of hitting melt holes in the ice surface. Ice on "C" lake shelf perimeters had melted, forming moats around the periphery of the thick ice covering the majority of the basin. The November and December decrease in rate of ice growth seen in Figure 42 is accentuated in Figure 43 for the Foothill lakes. The climatic extremes are greater at the southern end of the transect where continental climate predominates over the stabilizing influence of marine climate at the northern end.

The average ice thicknesses shown in Figures 41 through 43 vary most during December and January. On 1 January 1979 average ice thicknesses are 108 cm, 92 cm, and 72 cm for "A", "B", and "C" lakes, respectively. The curves for ice thickness come together, and by 1 April 1979 values are 166 cm, 162 cm, and 155 cm for "A", "B", and "C" lakes, respectively. Ice thickness obviously varies with time and climate along the study transect.

Combined Ice Thickness Data Sets across Transect. The data from Figures 41 through 43 have been combined in Figure 44 to illustrate the combined effects of climatic gradient in latitude and of time at monthly intervals along the study transect. The rationale for Figure 44

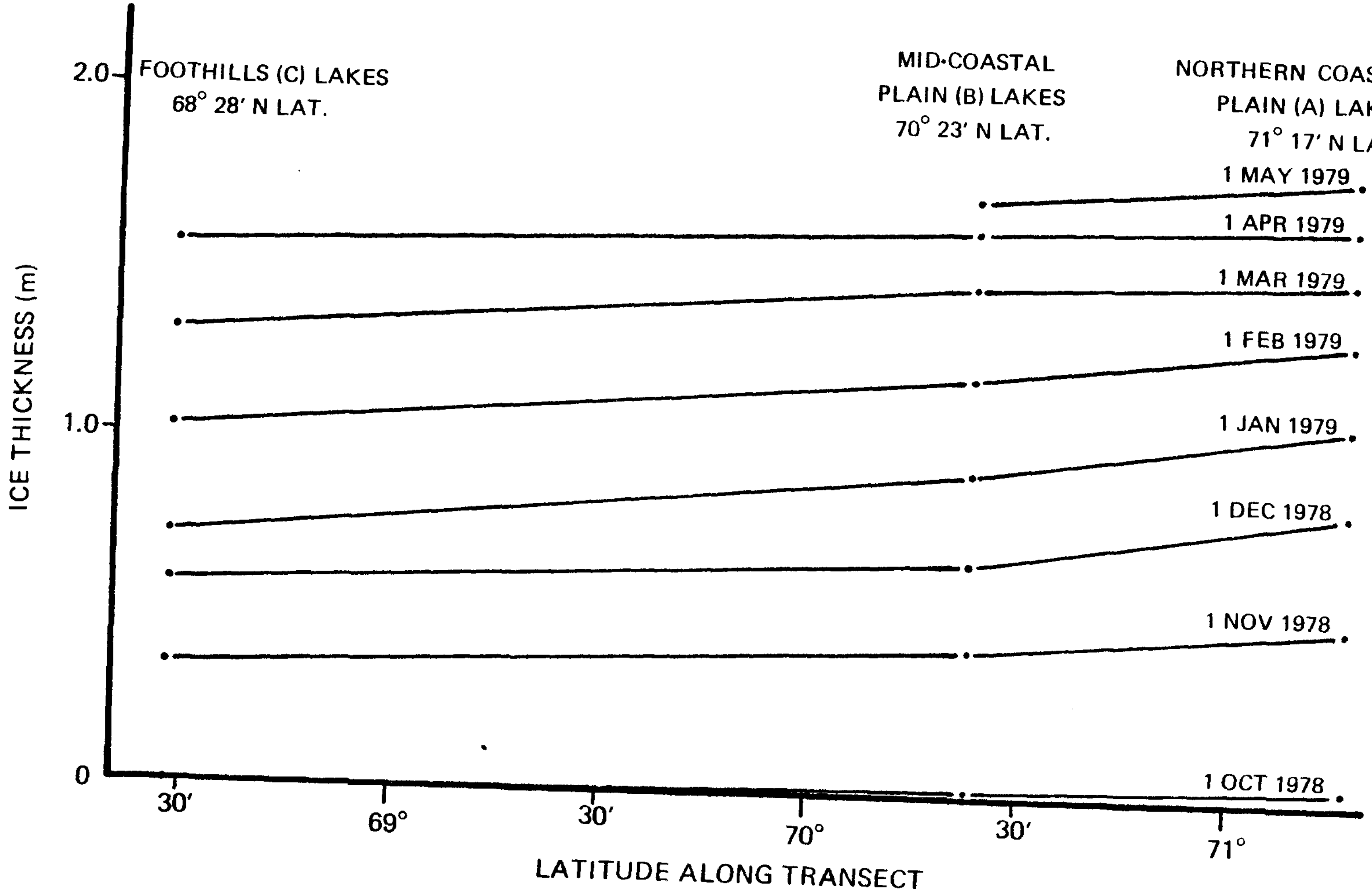


Fig. 44. Average ice thicknesses at 1-month intervals as a function of latitude along the study transect.

was to provide a means of estimating average ice thickness for any lake within the study transect throughout the winter of 1978-79 by interpolation of the specific date and latitude of interest. Figure 44 was used to estimate dates for resource associations with water depth in Chapter IV. Figure 44 data have also been used to estimate ice thickness used for SLAR image interpretations in Chapter II.

The average ice thickness for the first of each month was taken from Figures 41-43 and plotted relative to the mean latitude of the lakes measured within each of the 3 study areas C, B, and A. The lines connecting the plotted values represent the ice thicknesses along the entire transect for the first day of the month, indicated on the right side of Figure 44. Ice growth was greatest during October along the entire transect. Northern ice growth rates decreased with fairly equal regularity for each ensuing month. Ice growth rates at the southern end of the Transect were greatest during October and January with obvious changes in the rate of growth in intervening months.

Summer and Winter Data Summaries

Tables 3 and 4 summarize limnological data collected on the 9 study lakes during the summers of 1978 and 1979. These include maximum depth, specific conductance, suspended sediments, light attenuation, nutrients, zooplankton, fish, pH, alkalinity, dissolved inorganic carbon, and temperature. The chlorophyll *a*, primary production, and emergent vascular vegatation data have been summarized in Tables 3 and

Table 3. Summary of lake data, 5-25 Aug. 78.

Transect Lake Number	Sample Date 1978	Maximum Depth (meters)	Specific Conductance (μmhos/cm)	Suspended Sed. Load (mg/ℓ)	Secchi Disc. (meters)	1% Io (m)	CHLOROPHYLL *a* Range in Water Col. (mg/m^3)	CHLOROPHYLL *a* Range Benthic (mg/m^2)	NUTRIENT AVERAGES (μgat/ℓ=μmole/ℓ) NH_3	$NO_2 + NO_3$	NO_2	SiO_3	PO_4	ZOOPLANKTON COUNTS *Branchinecta*	Harpacticoida	Copepoda nauplii	*Cyclops* sp. (mostly immature)	*Cyclops bicuspidatus thomasi*	*Cyclops capillatus*	*Heterocope septentrionalis*	*Limnocalanus johanseni*	*Limnocalanus macrurus*	*Eurytemora canadensis*	*Diaptomus pribilofensis*	*Holopedium gibberum*	*Chydorus sphaericus*	*Bosmina longirostris*	*Daphnia longiremis*	*Daphnia middendorffiana*	FISH SAMPLED DURING SUMMERS 1977, 1978 AND 1979
NORTHERN COASTAL PLAIN LAKES																														
A-1	25 Aug	3.1	840	1.9	~3	~6	0.1	11.8	0.5	0.2	0.04	5.2	trace	-	-	-	32	-	-	-	-	55	-	23	-	-	-	-	105	None
							to	to																						
							0.4	80.4																						
A-2	5 Aug						0.7	6.0						-	-	>1000	-	344	-	3	-	-	-	-	-	-	-	404	-	Yes, ninespine stickleback and least cisco (sampled 4-5 August 1978).
	6	2.1	178				to	to																						
	25 Aug			5.2	1.75	3.5	1.0	45.0	0.2	0	0.02	15.9	0	-	-	>6000	-	540	-	-	-	-	-	-	-	-	-	6390	-	
A-3	22 Aug			105.0	<.25	<0.5	1.2	7.6						12	-	-	-	-	-	-	45	-	-	-	-	-	-	-	-	Not sampled, probably too shallow to support fishery, no inlet or outlet.
	&	1.2	500				to	to																						
	25 Aug			8.9	1.0	2	1.3	22.4	0.9	0.3	0.05	12.1	.04	15	-	<50	-	-	-	-	190	-	-	1	-	-	-	-	87	
MID-COASTAL PLAIN LAKES																														
B-1	23 Aug	11.5	190	1.1	5	10	0.6	1.6	0.1	0	trace	10.3	0	-	-	>500	14	-	-	-	-	-	197	-	-	22	4	8	-	Yes, ninespine stickleback and least cisco (sampled August 1979).
							to	to																						
							1.8	61.8																						
B-2	23 Aug	1.9	69	1.8	>2	>4	0.8	3.8	0.3	0	0.02	8.9	0	-	-	>500	106	-	-	204	-	-	-	14	-	14	2	-	-	Yes, ninespine stickleback (sampled August 1979).
							to	to																						
							1.2	44.4																						
B-3	23 Aug	0.45	77	very clear	>1	>2	1.3	5.5	0.8	0	0.03	12.2	0	-	5	-	6	-	-	-	-	-	-	-	-	-	-	-	-	Possibility for some ninespine sticklebacks from deep adjacent lake as seen in march area surrounding pond (none sampled).
								to																						
								9.9																						
FOOTHILL LAKES																														
C-1	24 Aug			3.8	1.8	3.6	1.2	1.3	0.6	0	0.06	1.9	0	-	-	-	>1500	-	-	10	-	-	-	16	-	-	-	-	-	Yes, lake trout, arctic grayling, broad white-fish (sampled ADF&G, 1977).
	&	6.8	38				to	to																						
	12 Aug			3.3	1.5	3	5.8	29.8						-	-	<50	-	-	644	8	-	-	-	14	-	-	-	-	-	
C-2	24 Aug			5.2	1.5	3	3.5	3.3	1.3	0.4	0.08	2.0	.05	-	-	-	64	-	-	-	-	-	-	986	30	-	-	-	-	Not sampled, probably too shallow to support fishery, no inlet or outlet.
	6	2.0	32				to	to																						
	12 Aug			8.0	1.5	3	4.0	73.3						-	-	-	-	-	48	2	-	-	-	2726	112	-	-	-	-	
C-3	24 Aug	1.1		30.2	.25	.5	10.0	37.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Not sampled, probably too shallow to support fishery, no inlet or outlet.
								to																						
								49.5																						

Table 4. Summary of lake data, 7-11 Aug. 79.

Transect Lake Number	Maximum Depth	Specific Conductance (µmhos/cm)	Suspended Sediment Load (mg/ℓ)	Light Attenuation 1%Io (m)	Light Attenuation (k)	CHLOROPHYLL A RANGES, Water Column: Vertical Prof. (mg/m^3) min.	CHLOROPHYLL A RANGES, Water Column: Vertical Prof. (mg/m^3) max.	CHLOROPHYLL A RANGES, Water Column: Horizontal Transect (mg/m^3) min.	CHLOROPHYLL A RANGES, Water Column: Horizontal Transect (mg/m^3) max.	CHLOROPHYLL A RANGES, Benthic: (mg/m^2) at 1/2 m	CHLOROPHYLL A RANGES, Benthic: (mg/m^2) /at deep (m)	PRIMARY PRODUCITON, Water Column: ($mgC/m^3 \cdot day^1$) at 1/2 m	PRIMARY PRODUCITON, Water Column: ($mgC/m^3 \cdot day^1$) /at deep (m)	PRIMARY PRODUCITON, Benthic: ($mgC/m^2 \cdot day^1$) at 1/2 m	PRIMARY PRODUCITON, Benthic: ($mgC/m^2 \cdot day^1$) /at deep (m)	pH	Alkalinity (mg/ℓ)	Dissolved Inorg. Carbon (mg/ℓ)	NUTRIENTS (µgat/ℓ=mole/ℓ): NH_3	NUTRIENTS: $NO_2 + NO_3$	NUTRIENTS: NO_2	NUTRIENTS: SiO_3	NUTRIENTS: PO_4	Surface Temp. (°C) 9 & 10 Aug.	VASCULAR AQUATIC VEGETATION: *Arctophila fulva*	VASCULAR AQUATIC VEGETATION: *Carex aquatilis*	VASCULAR AQUATIC VEGETATION: *Dupontia fisheri*
NORTHERN COASTAL PLAIN LAKES																											
A-1	3.1	730	1.78	7.1	.65	.05	.50	.02	.67	-	250/3m	20	3/3m	-	84/3m	7.41	52.6	13.9	.2	.1	.04	13.0	.02	6.2	X	-	X
A-2	2.1	187	3.30	6.3	.73	.06	.23	<.01	5.05	40	210/2m	40	43/2m	8	5/2m	6.60	7.5	3.0	.1	trace	.03	-	0	7.8	X	-	-
A-3	1.2	460	39.80	1.4	3.34	.14	.21	.21	2.83	20	40/1m	17	3/1m	-	1/1m	6.60	7.4	3.0	.5	.1	.06	10.9	.01	-	X	-	X
MID-COASTAL PLAIN LAKES																											
B-1	11.5	155	1.54	8.5	.53	<.01	.43	<.01	<.01	10	150/8m	11	-7/11m	12	788/2m 24/8m	7.60	69.4	17.8	.2	.1	.01	18.1	0	12.1	X	X	-
B-2	01.9	63	2.16	5.4	.78	.28	.43	.28	.68	10	270/2m	51	65/2m	120	493/2m	6.99	14.4	4.4	.1	trace	.02	15.9	trace	14.4	X	X	-
B-3	0.45	56	5.70	>3	-	.10	.10	.10	.10	70/.3m	-	44	44/.5m	385	385/.5m	6.96	12.7	3.6	.6	.1	.06	6.9	.03	15.7	X	X	-
FOOTHILL LAKES																											
C-1	6.8	26	2.56	3.6	1.24	3.50	3.76	2.85	8.70	10	60/4m	67	3/4m	196	2/4m	6.51	7.5	3.7	.3	.1	.05	11.5	.03	15.2	X	-	-
C-2	2.0	17	5.10	2.7	1.72	3.04	3.04	2.46	6.37	50	260/2m	180	64/2m	84	103/2m	5.90	3.0	3.2	.6	.1	.06	10.2	.04	14.8	X	X	-
C-3	1.1	40	18.36	1.2	3.84	20.15	22.75	22.10	24.05	-	140/1m	142	45/1m	125	41/1m	6.70	14.8	5.4	.4	trace	.08	14.7	.06	15.2	X	X	-

X = Major species found lake vegetation transect.

4 to facilitate comparison with other data even though more detailed graphs follow.

The lakes took on a different character when ice and snow covered them. Snow and ice cover in the Arctic persists for about 9 months, during which light penetration is reduced, and atmospheric oxygen is prevented from reaching the water. Less light penetration reduces photosynthesis. These factors contribute to reduced dissolved oxygen levels. Some lakes become severely deoxygenated. Dissolved solids are concentrated into free water beneath the ice cover. Water temperatures cool throughout the winter months to within a degree or 2 of freezing. Wind mixing of the water column is stopped with the arrival of ice cover, and mixing is relegated to the less dynamic process of convection.

Data acquired from ice-covered study lakes during April 1980 are summarized in Table 5 for comparison with summer data and in a format similar to Tables 3 and 4. Only lake numbers 1 and 2 from each area were sampled because the shallow number 3 lakes were frozen to the bottom. Data on dissolved oxygen, ice thickness, and snow cover were obtained on the study lakes during March, April, and May of 1979. These data and specific conductance data throughout the entire winter 1978-79 are also illustrated in this chapter.

Ice and Snow Cover

Ice and snow cover measurements were taken on study lakes during April of 1980 and are included in Table 5 to describe lake cover conditions that prevailed at the sample locations.

Table 5. Data obtained from ice-covered lakes 7-15 Apr. 80.

Study Lake Number	Sample Date April 1980	Water Column Measurements Below Ice Cover: Dissolved Oxygen (ml/ℓ)		Temperature (°C)		Specific Conductance (μmhos/cm)	Chlorophyll *a* in Water Column (mg/m^3)	NUTRIENTS (μgat/ℓ = μmole/ℓ): NH_3	$NO_2 + NO_3$	NO_2	PO_4	Ice and Snow Measurements: Ice Thickness (cm)		Snow Depth (cm)		No. of Holes Drilled	% Snow Cover
		I/W	W/S	I/W	W/S							Ave	Range	Ave	Range		
NORTHERN COASTAL PLAIN LAKES																	
A-1	15	2.1	1.8	0.1	0.1	2310	2.1 & 17.9	33.1 & 28.7	3.2 & 4.8	0.42 & 0.37	0.35 & 0.15	190	167-210	10	0-21	5	98
A-2	7	-	-	-	-	624	0.2	16.8	8.1	2.48	0.20	146	142-153	29	26-33	4	100
MID-COASTAL PLAIN LAKES																	
B-1	8	3.3	1.3	0.5	2.0	328	1.2	1.1	14.0	0.27	2.65	156	153-160	15	14-16	4	99
B-2	8	0.9	0.8	0.5	0.5	320	3.2	25.0	0.3	0.46	0.85	144	143-145	27	22-32	2	100
FOOTHILL LAKES																	
C-1	8	8.5	1.5	0	2.7	70	2.8	1.4	10.2	0.35	1.15	170	156-179	10	9-12	4	99
C-2	14	4.5	4.5	0.6	0.6	72	1.4	3.9	29.3	1.29	3.20	132	131-133	30	26-36	4	100

I/W = Ice/Water Interface
W/S = Water/Substrate Interface

The data, although limited in temporal variation and number of samples, portray some general trends. The average ice thickness on medium depth lakes was thickest on A-2 (146 cm), was 144 cm on B-2, and was thinnest on C-2 (132 cm). The snow cover was similar on these 3 lakes with averages ranging from 27 to 30 cm deep. The 3 deep lakes had a variety of snow and ice cover conditions. Lake B-1 had considerably less ice (156 cm) than did A-1 or C-1 because it had a thicker average snow depth (15 cm versus 10 cm). Lake A-1 had 190 cm average ice thickness while C-1 had 170 cm. Both lakes A-1 and C-1 had an average snow depth of 10 cm, which relegated the differences in their ice thickness to the climatic gradient.

Temperatures

The surface temperatures of the study lakes were measured on 9 and 10 August 1979. The 2 day sampling time frame does not permit a perfectly synoptic view but was the best logistic compromise to provide data that could be compared across the 300 km transect. The results are listed in Table 4.

The surface water temperatures ranged from 6.2°C in Lake A-1 to 15.7°C in Lake B-3. Lake A-1 was expected to have had the lowest of temperatures because it was the most northerly and was the deepest "A" lake. Pond B-3 was not the most southerly, but it had the shallowest basin studied. Summer temperatures as high as 17°C have been measured in shallow ponds near Barrow. An increase in temperature with decreasing maximum water depth was evident in both "A" and "B" lakes. Very little lake to lake surface temperature variation was present during the sampling of the "C" lakes. These surface water temperatures were acquired mid-day during the warmest period of summer, and the shallowest lakes had the highest temperatures. The shallow basins sustain the greatest diurnal and seasonal variations/extremes in temperature. The mean August 1979 temperature for "A" lakes was 7.0°C, with a standard deviation of 1.1°C. The mean temperature for "B" lakes was 14.1°C, with a standard deviation of 1.8°C. The mean temperature for "C" lakes was 15.1°C, with a standard deviation of 0.2°C. The effect of the climatic gradient is evident.

The summer surface water temperatures of the study lakes varied both with maximum lake depth and climatic gradient.

The circulation of most Arctic lakes has been described as monomictic (one period of complete circulation annually). This is a Likens and Johnson (1968) modification of the Hutchinson (1957) definition of a cold monomictic lake in which 1 period of complete mixing occurs during the summer at water temperatures below 4°C. Instead, most Arctic lakes appear to mix throughout the summer, but water temperatures become greater than 4°C. The absence of thermal stratification in these lakes is due primarily to shallow water depth and persistent winds.

Temperature values relative to the snow, ice cover, and water depth at each April 1980 lake sampling point are illustrated in Figure 45. The thermal gradient was largest in Lake C-1, which had a temperature of 0°C at the ice/water interface and 2.7°C near the water/substrate interface (Table 5 and Figure 45). The shallow lakes, with free water

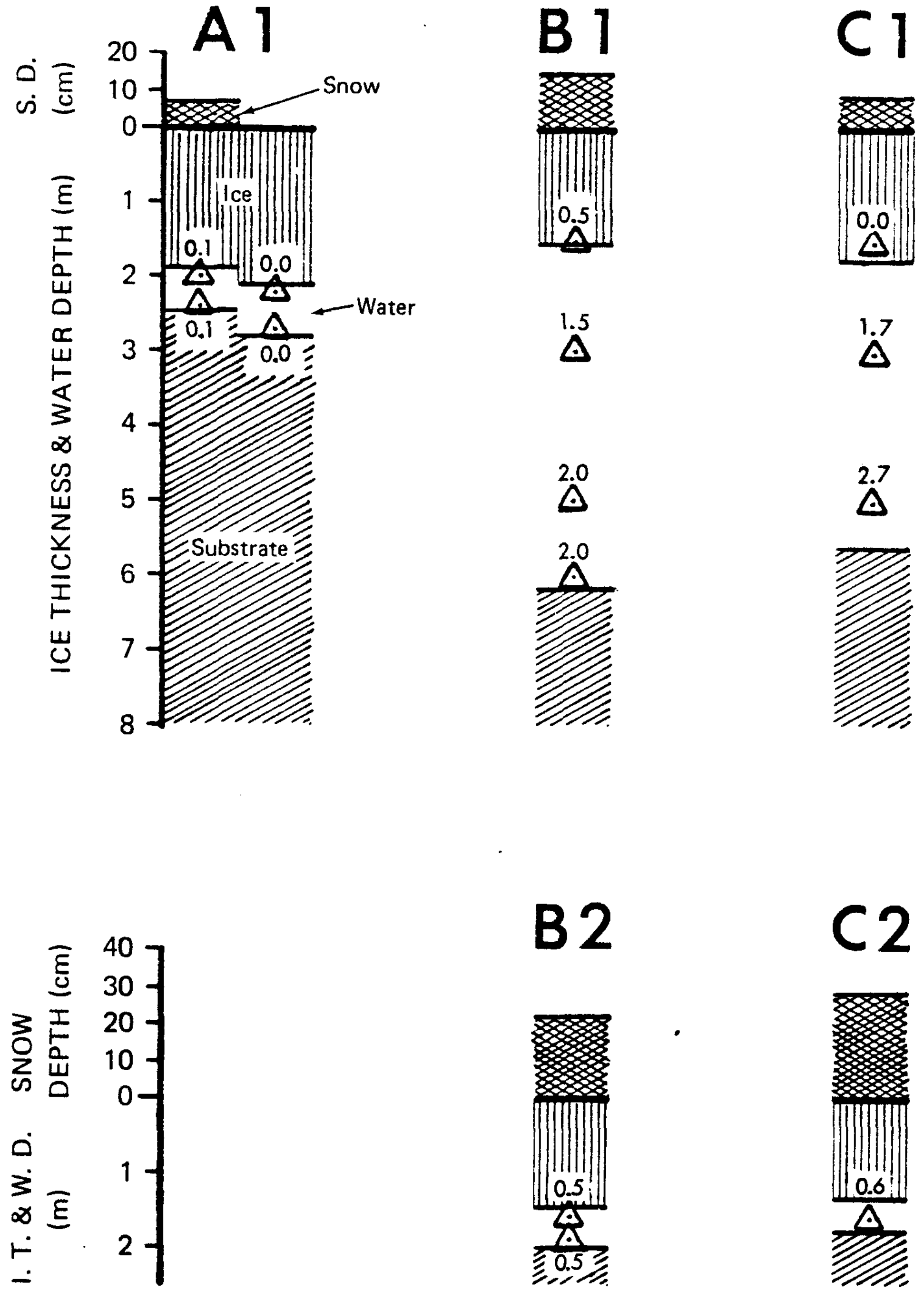


Fig. 45. Temperatures (°C), measured in the 8-15 April 1980 water column of study lakes, illustrated relative to snow and ice over the area sampled and proximity to ice/water and water/substrate interfaces.

restricted to less than 1 m depth, were isothermal and had low temperatures of between 0°C and 0.6°C. Insufficient measurements were acquired to be confident in relating April temperature differences to the gradient in latitude; however, the water temperatures were slightly higher as I moved south along the study transect.

The April data also show that shallow lakes with limited volumes of free water were cooled to a greater extent than were deep lakes containing large volumes of thermally stratified water. The spring water temperatures are another characteristic that can be related to maximum lake depth, in addition to specific water depths within an ice-covered lake.

Brewer (1958) and Likens and Johnson (1968) have studied the thermal regime of a few arctic lakes. Brewer's classic work on Imikpuk Lake (A-1) describes the annual thermal cycle in both the water and sediment columns. The lake bottom sediments store heat in the summer and are a source of heat beneath ice and snow cover in the winter. Brewer estimated that 82% of the heat absorbed during 1954 was used to melt winter ice cover, leaving only 18% to raise the temperature of the water column. Two reasons exist for early rapid melt of shallow basins frozen to the lake bottom. The ice cover frozen to the bottom never reaches the extent found in deeper lakes; hence, because less ice forms there is less to melt. Second, the melting process for ice frozen to the lake bottom progresses differently from that of ice that floats free of the bottom. Ice floating free of the bottom maintains a freeboard so that water melting on the surface flows off the surface, leaving a surface with high albedo that reflects a substantial amount of solar radiation. The ice on a shallow lake or pond that is frozen to the bottom tends to collect and retain water melting on the surface because that water has nowhere to go. The surface albedo reduced by the puddled surface water, absorbs rather than reflects solar radiation, and heat is absorbed by the dark underlying sediments. This speeds the melting process; therefore, ice on the shallowest puddles, ponds and lake shelves melts most rapidly in the spring. Once the ice is melted, the energy goes into heating and raising water and bottom substrate temperatures in the shallow water bodies.

Suspended Sediments

Water samples were collected from the surface water of the 9 study lakes for gravimetric determination of suspended sediment load (SSL) during August of 1978 and 1979 (Tables 3 and 4). Suspended sediment load measurements were acquired on 2 different days during August 1978, and in study lakes, ranged from a low of 1.1 mg/ℓ in B-1 to a high of 105 mg/ℓ in wind-stirred Lake A-3. The shallow lakes have the highest values and greatest fluctuation in SSL. A mean and standard deviation were calculated for shallow, 2 m, and then for deep lakes, using all SSL data collected in 1978 and 1979. The mean for shallow lakes A-3, B-3, and C-3 was 34.66 mg/ℓ, with a standard deviation of 36.77 mg/ℓ. Lake A-3 had the greatest variation, with values of 8.9 and 105 mg/ℓ in 1978 and 39.8 mg/ℓ in 1979. This is a result of its shallow depth, large area and fetch, and persistent winds on the Northern Coastal

Plain. The mean for 2 m deep lakes A-2, B-2, and C-2 was 4.39 mg/ℓ, with a standard deviation of 2.15 mg/ℓ. The deep lakes A-1, B-1, and C-1 had the least SSL and/or variation in SSL with time. The mean was 2.28 mg/ℓ, with a standard deviation of 0.98 mg/ℓ for the 1978 and 1979 data collected (Tables 3 and 4). Lake depth is a strong factor in the SSL found in a water body, but wind, surface area, and substrate type are also factors. For example, the SSL's in B-3 were considerably less than those in A-3. Pond B-3 has a small area, less wind, and a firm sandy substrate in contrast with A-3's large area, persistent exposure to wind, and soft fine sediments. Likewise, the SSL in B-2 was less than that in A-2. Lake A-2 has a surface area 5 times that of B-2, and B-2 has an extensive shallow (0.5 m) sandy shelf area. The primary factors creating greater SSL's in Northern Coastal Plain "A" lakes compared with Mid-Coastal Plain "B" lakes is the persistent wind-generated waves that continually resuspend the "A" lake substrates. The Foothill "C" lakes also have greater SSL than do "B" lakes. This is due to the humic matter and higher phytoplankton standing crop which are discussed in the chlorophyll *a* results. Lake C-3 had both the highest water column chlorophyll *a* of all study lakes and the highest SSL (30.2 mg/ℓ in 1978 and 18.4 mg/ℓ in 1979) of the "C" lakes.

Changes in suspended sediment loads are attributable to both water depth and climatic gradient in the study lakes.

Light Attenuation

Light attenuation, which was sampled at the same time and place as SSL, was measured with a photometer in 1979 (Table 4) and was estimated by Secchi disc in 1978 (Table 3). The 1979 *in situ* photometer measurements were plotted on semilog paper to determine both the 1 percent incident light level (1% Io) in meters and the extinction coefficient (k). These are reported in Table 4. Light attenuation estimates obtained in 1978 are reported as Secchi disc readings in meters in Table 3 and have been converted to 1% Io for comparison with the values in Table 4. The Secchi disc values have been multiplied by a factor of 2 (Lind 1979) to provide a gross estimate of photic depth (1% Io).

The 1% Io occurrence ranged from a minimum of 0.5 m in lakes C-3 (1978) and A-3 (1978) to a maximum of 8.5 m in Lake B-1 (1979). Light attenuation is inversely proportional to the SSL, and as would be expected, those lakes with high SSL had a shallow 1% Io. Light attenuation estimates provide semiquantitative information about a lake, although their ability to describe the underwater light climate for plankton is questionable. Additional information such as surface solar radiation input and depth of mixing is necessary (Talling 1971).

Changes in light attenuation are attributable to both water depth and climatic gradient in the study lakes, for the same reasons as those described for variations in SSL.

Specific Conductance

Specific conductance samples collected from each of the 9 study lakes during August 1978 and 1979 (Tables 3 and 4) ranged from a minimum of 17 μmhos in a Foothill Study Lake C-2 to a maximum of 840 μmhos in a Northern Coastal Plain Study Lake A-1. The "A" lakes had the widest range of specific conductance values. Lake A-2, located about 6 km from the marine environment, had specific conductance values of 178 to 187 μmhos. A-1 and A-3, situtated immediately adjacent to saltwater, had values of 730 to 840 μmhos and 460 to 500 μmhos, respectively. The mean specific conductance for "A" lakes was 481 μmhos, with a standard deviation of 274 μmhos. These lakes have high dissolved solid concentrations and variability resulting from small changes in their proximity to the marine environment. The "B" lake specific conductances ranged from 56 to 190 μmhos, with a mean of 102 μmhos and a standard deviation of 56 μmhos. The "C" lakes had the lowest specific conductances, which ranged from 17 to 40 μmhos. The mean for "C" lakes was 31 μmhos, with a standard deviation of 9 μmhos. The changes in specific conductance are a function of their distance from the marine environment that is contributing chloride ions to the study lakes. Holmquist (1975), Sloan (unpublished), and National Petroleum Reserve in Alaska Task Force (1978) have also surveyed Arctic lakes showing these same dissolved solid trends. No change in summer specific conductance related to lake depth was noted. Summer density stratification (i.e. dissolved solids and temperature) is not prevalent in shallow arctic lakes.

Specific conductance measurements were also acquired from the study lakes throughout the winter of 1978-79 and in April 1980. The April 1980 values are summarized in Table 5 and clearly illustrate the decreasing values encountered with the decreasing latitude of lake areas "A", "B", and "C". The summer 1978 and 1979 data (Tables 3 and 4) show the same relationship, but less dramatically, as the salts are mixed through the entire water column of the lake. The April ice cover concentrates the salts in the water below the ice, causing much higher specific conductance values in the spring than at other times of the year.

Figure 46 illustrates the change in specific conductance of study lake waters, beginning at freeze over and ending just prior to break-up. The specific conductance values at the far left of Figure 46 are actually the summer values acquired in August but are illustrated at the date of freeze over in late September or early October. The specific conductance does not change substantially during the ice-free season.

The most rapid increase occurred in March and April for most study lakes (Figure 46). This spring increase was most dramatic in lakes A-2, B-2, and C-2 because the volume of free water beneath the ice was small and the salts rejected from newly formed ice were rapidly concentrated. Lakes B-1 and C-1 had a large volume of water beneath the ice into which salts were rejected and diluted. The summer values for B-2 and C-2 were lower (i.e. 69 and 32 μmhos, respectively) than B-1 and C-1 (i.e. 190 and 39 μmhos, respectively). The salts were concentrated in the small volumes of water in B-2 and C-2. By spring, specific conductances in B-2 and C-2 were larger 654 and 133 μmhos, respectively, compared with 396 and 71 μmhos for B-1 and C-1. Lake C-3 was the only shallow lake from which a specific conductance sample was collected after freeze over. The specific conductance value from a November 1978 sample showed a threefold increase over the summer value. Lakes with a maximum depth of 1 m (i.e. A-3 and C-3) were frozen to the bottom by February, concentrating the salts near the substrate interface. In

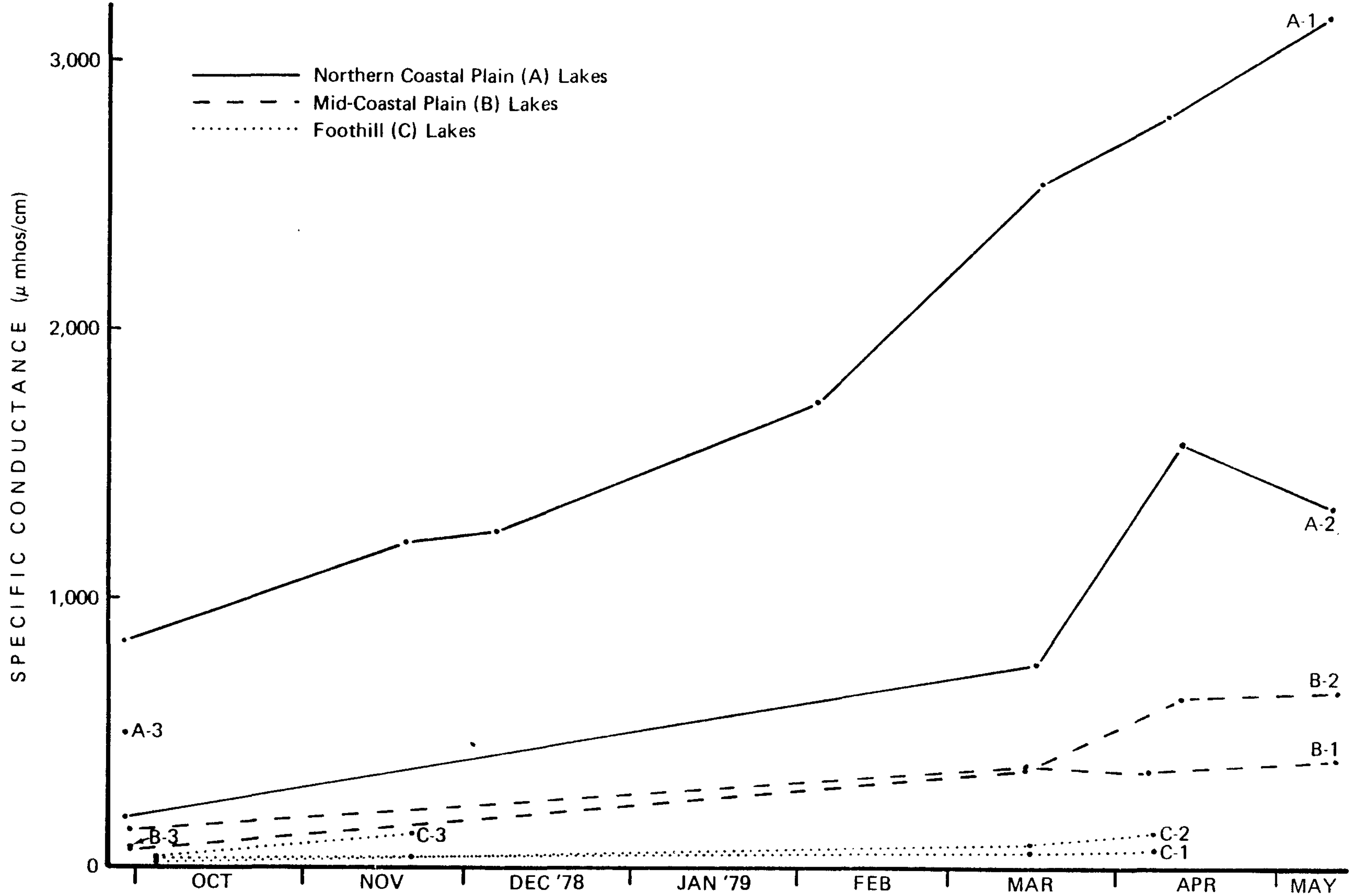


Fig. 46. Seasonal variation of specific conductance in study lakes during the winter 1978-79.

August 1978, Lake A-1 had a specific conductance of 840 μmhos that increased to 3,160 μmhos by May 1979 at maximum ice thickness.

Both summer and winter results show a relationship between the latitude of lakes within the study transect (proximity to marine environment) and specific conductance. Specific conductance is highest in northern lakes near the coast and lowest in lakes to the south. Lake depth also affects specific conductance. In shallow lakes dissolved solids become more concentrated, increasing the specific conductance rapidly as water volume remaining under lake ice cover decreases during the winter.

pH, Alkalinity and Dissolved Inorganic Carbon

The pH, alkalinity, and dissolved inorganic carbon (DIC) measurements were collected for and used in the 1979 primary production calculations. These measurements are summarized with other 1979 data in Table 4. In areas "A" and "B" the deepest lakes, A-1 and B-1, had higher pH (7.41 and 7.60), alkalinity (52.6 and 69.4 mg/ℓ) and DIC (13.9 and 17.8 mg/ℓ, respectively) than did the shallow lakes. Values ranged for the shallow lakes A-2, A-3, B-2, B-3 from 6.60 to 6.99 for pH, from 7.4 to 14.4 mg/ℓ for alkalinity, and from 3.0 to 4.4 mg/ℓ for DIC. The pH, alkalinity, and DIC in the "C" lakes were in a narrower range of values, with C-1 much lower than B-1 and A-1. Values for "C" lakes ranged from 5.90 to 6.70 for pH, from 3.0 to 14.8 mg/ℓ for alkalinity and 3.2 to 5.4 mg/ℓ for DIC.

The scope of data was insufficient to make definite correlations between data variables and water depth or climatic gradient.

Dissolved Oxygen

Dissolved oxygen (DO) measurements were taken only during the ice covered period, but wind mixing probably keeps summer dissolved oxygen levels near saturation in most of the arctic lakes. As dissolved oxygen is excluded from water forming ice, high oxygen concentrations and even supersaturation can be expected in arctic lakes soon after freeze over. High concentrations continue to prevail until the concentrating effects of ice accretion fall short of oxygen depletion through respiration. Rapid formation of ice may result in the removal of gases, including oxygen, from the water column. The gases come out of solution in the form of bubbles that become entrained in the ice cover.

Dissolved oxygen samples were acquired through holes in study lake ice covers during March, April, and May 1979. Only a few samples were acquired, as winter field conditions were not conducive to Winkler wet chemistry methods (see Methods). Each set of DO samples was specific to a set of conditions (i.e. date, lake, geographic location on the lake surface, lake depth at the ice hole, ice thickness, and snow cover) encountered at the time and place measurements were taken. The conditions specific to the lake area sampled have been illustrated relative to the DO values and water depth in which they were acquired (Figure 47). In most cases the DO is least where free water is restricted to a small amount of space between ice cover and substrate. This was not the case

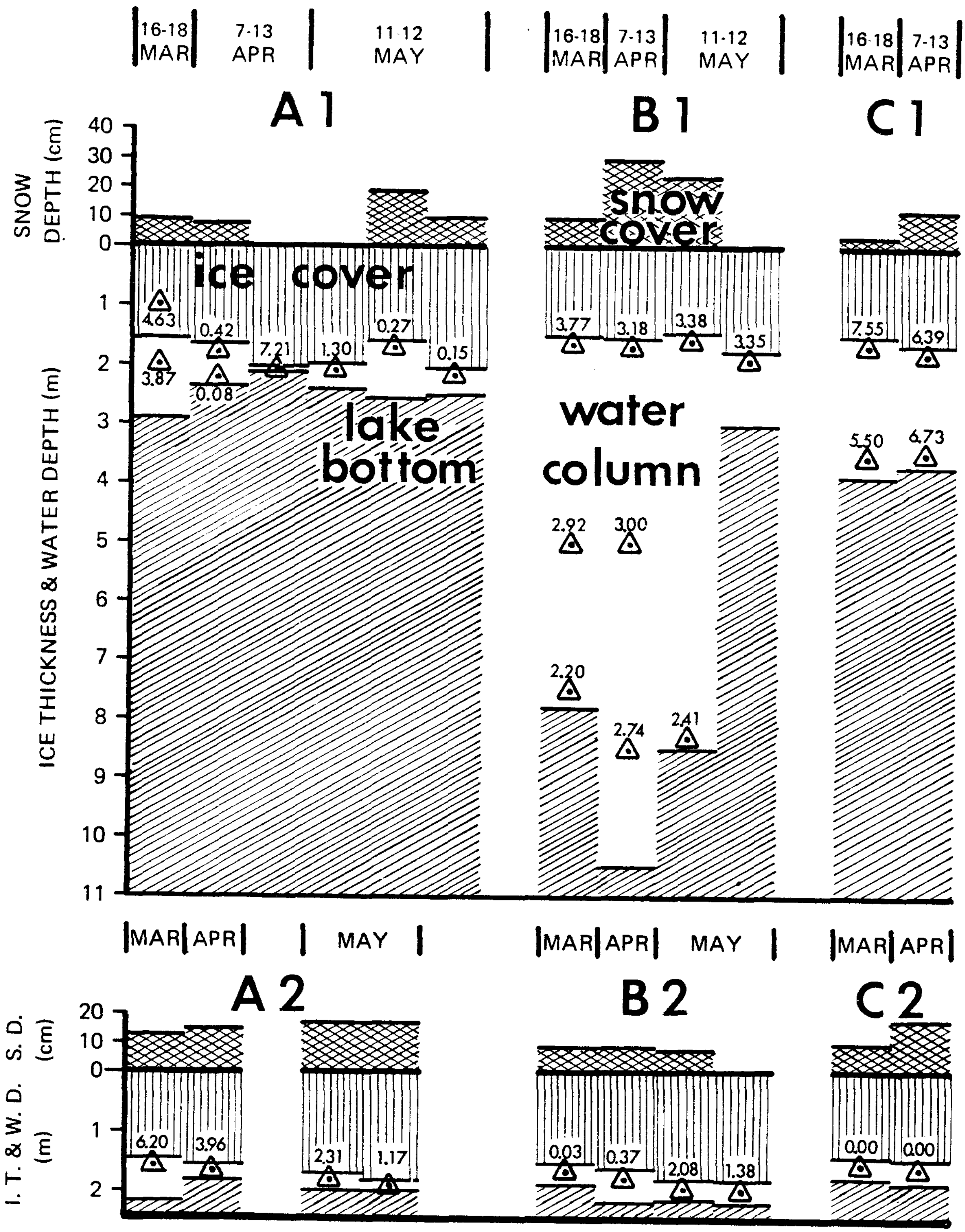


Fig. 47. Dissolved oxygen (ml/ℓ), collected March-May 1979, from the water column of study lakes, illustrated relative to sampling dates, snow and ice over area sampled, and proximity to ice/water and water/substrate interfaces.

in Lake A-1 in April, when a value of 7.21 ml/ℓ was acquired in only 10 cm of water. The reason for this high DO was the lack of snow cover which had prevailed through the winter in the part of the lake sampled which had algae present. The algae were retrieved in photosynthetically active condition from the same auger hole as the DO sample. This area was sampled because of its atypically snow-free condition, caused by a prevailing wind air burble from a building adjacent to Lake A-1. The wind continually scours the ice surface free of snow, thus permitting much more light to reach the ice/water interface and algae growing there. All remaining DO profile values depicted in Figure 47 decrease with increasing depth in a lake and with proximity to benthic substrates.

Dissolved oxygen measurements were acquired again in April 1980 (Table 5). The measurements were taken with a DO meter, avoiding the winter hardships of Winkler wet chemistry, and requiring only that a DO probe be kept above freezing. The study lakes data are illustrated in Figure 48. The 1979 and 1980 DO values are similar (Figures 47 and 48), with the exception of Lake C-2. In this Lake the DO was 0 ml/ℓ in both March and April 1979, with snow cover from 10 to 20 cm. Yet Lake C-2 had a DO of 4.5 ml/ℓ under almost 30 cm of snow in April 1980. The 1979-80 winter was less severe than the 1978-79 winter; therefore, less ice formed, and every study lake measured during April of 1980 had a higher DO value.

Other arctic lakes in addition to study lakes were measured for DO during April 1980. The DO relationship to lake depth is illustrated with a larger number of samples in Figure 49. Six deep lakes (⩾ 4 m)

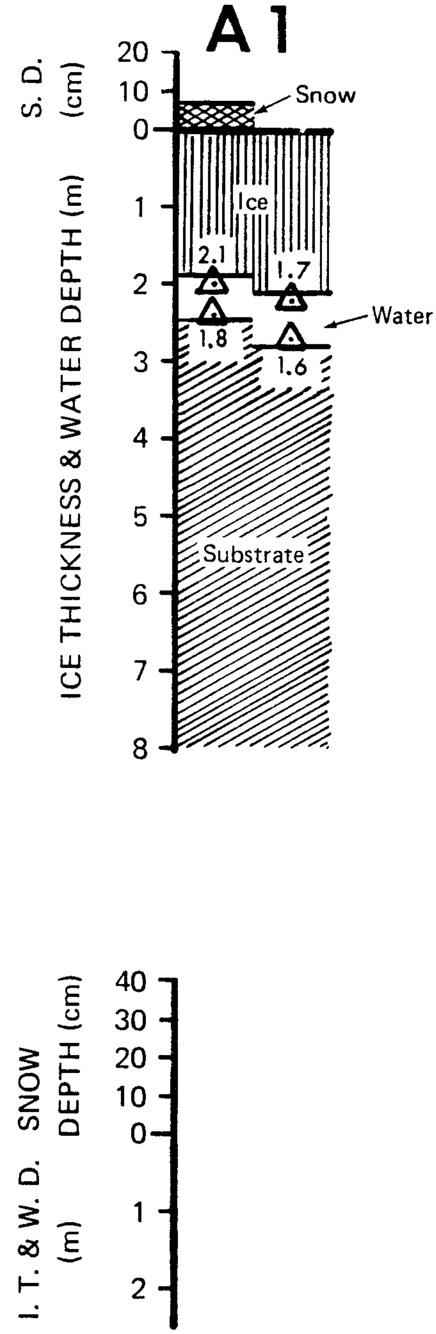


Fig. 48. Dissolved oxygen (ml/ℓ), collected from the 8-15 April 1980 water column of study lakes, illustrated relative to snow and ice over the area sampled and proximity to ice/water and water/substrate interfaces.

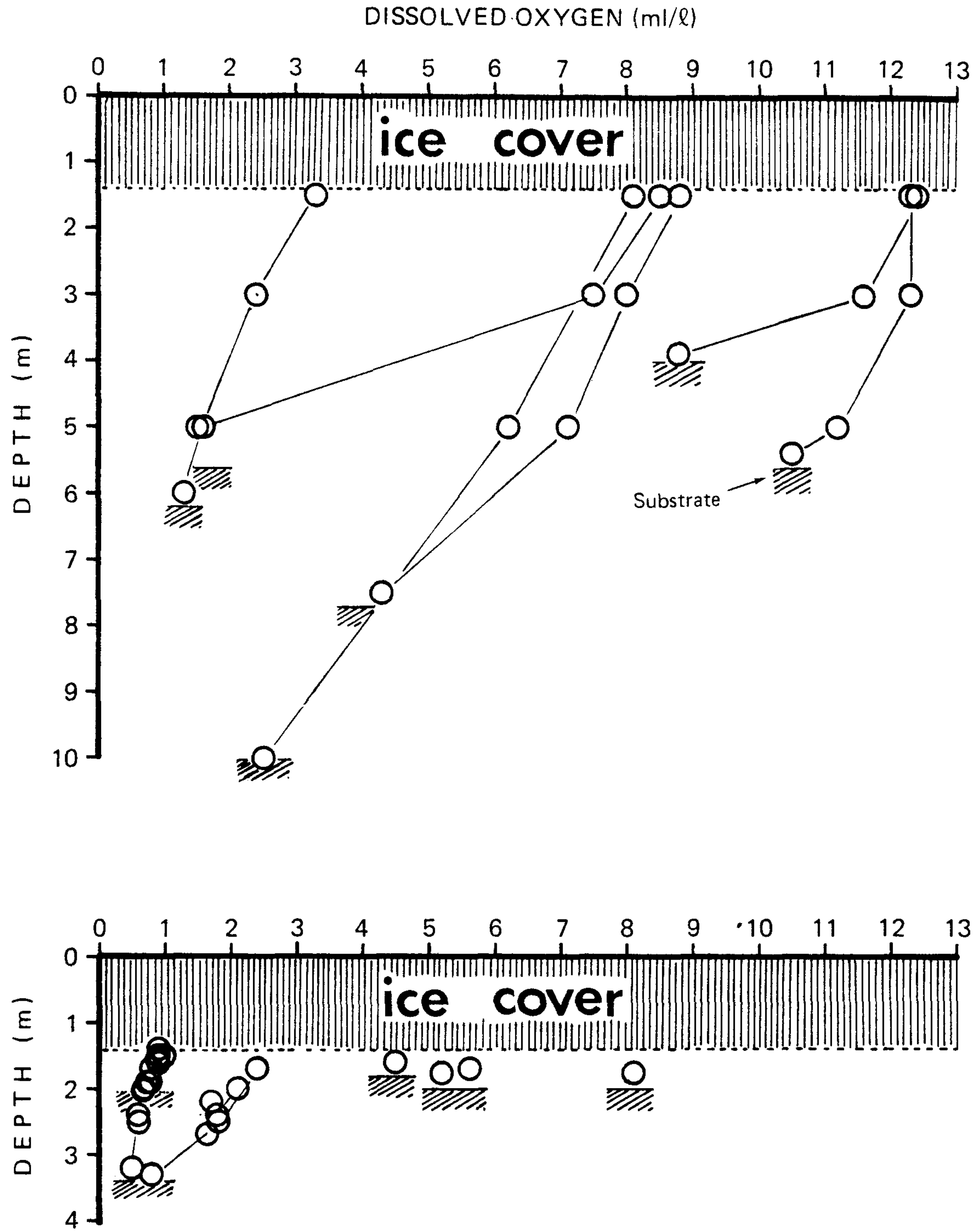


Fig. 49. Dissolved Oxygen (DO) measurements acquired in Alaskan arctic lakes under an April 1980 ice and snow cover. Lakes had observed substrate depths ⩾ 4 m (top) and < 4 m (bottom). Most substrate depths are illustrated below deepest, respective DO values.

are compared with 13 shallow lakes (< 4 m). Ice cover averaged about 1.4 m. Variations in ice cover and snow depth are not illustrated, but the substrate depth for each lake DO profile is shown below the last DO profile measurement when possible. Seven lakes with depths of approximately 2 m were measured and had low DO values of about 1 ml/ℓ or less. Within the 13 lakes that were < 4 m in depth only 4 lakes had DO values > 3 ml/ℓ. The 6 profiles in lakes ⩾ 4 m in depth all had DO values > 3 ml/ℓ, and 5 of the 6 had values > 8 ml/ℓ.

The dissolved oxygen values collected for ≈ 2 m deep study lakes A-2, B-2, and C-2 in 1979 (Figure 47) show a correlation with climatic gradient. The water is equally limited in space in these lakes; therefore, the differences in dissolved oxygen concentrations among lakes, for the most part, is attributable to respiration and microbial oxidation of the previous summer production of organic matter. Winter nutrient data were not available for correlation with winter 1978-79 dissolved oxygen data; however, from summer chlorophyll *a* values of the study lakes and summer and winter observations of brown/humic water in "C" lakes, we may conclude that "C" lake winter organic concentrations were high. Dissolved oxygen concentrations went to 0 ml/ℓ in Lake C-2, to < 1 ml/ℓ in B-2, and were ⩾ 4 ml/ℓ in A-2 during March and April 1979 (Figure 47). The relative potential for increased eutrophication in lakes on the southern end of the study transect may contribute to winter dissolved oxygen depletion, but restriction of water depth in shallow lakes appears to be an important factor.

Eutrophication due to waste disposal could certainly reduce winter dissolved oxygen levels in any shallow arctic lake.

Nutrients

A nutrient sample was collected from the surface (0.5 m depth) of each study lake during the month of August in both 1978 and 1979. The results are compiled in Tables 3 and 4 for comparison of variations in nutrients attributable to the maximum depths and climatic gradient of the study lakes.

Ammonia ranged from a low of 0.1 μg at/ℓ in B-1 (1978) to a high of 1.3 μg at/ℓ in C-2 (1978). Nitrate and nitrite were highest in lakes C-2 (1978 and 1979), A-3 (1978 and 1979), and B-3 (1979). Silicate was lowest (1.9 μg at/ℓ) in C-1 (1978) and was highest (18.1 μg at/ℓ) in B-1 (1979). Orthophosphate was low throughout all the study lakes, ranging from 0 to 0.06 μg at/ℓ. The highest values occurred in the shallowest lakes, A-3 (0.04 μg at/ℓ in 1978), B-3 (0.03 μg at/ℓ in 1979), C-3 (0.06 μg at/ℓ in 1979), and C-2 (0.05 μg at/ℓ in 1978 and 0.04 μg at/ℓ in 1979). No correlation with climatic gradient was obvious in the results. Nutrients may become limited through sediment retention (Prentki 1976). Resuspension of nutrient-enriched sediments may be one mechanism that increases nutrient concentrations in the shallow lakes.

Nutrient investigations in arctic lakes have been part of many aquatic studies (e.g. Hobbie 1962, Kalff 1968 and 1974), but a few have had the primary objectives revolve around nutrient dynamics

(Barsdate and Prentki 1972, 1973, and 1974, Prentki 1976). The general agreement is that phosphorus is the limiting nutrient, although inorganic nitrogen is also found in very low concentrations.

The nutrient concentrations were about an order of magnitude greater in April than in August. April ammonia concentrations ranged from 1.1 to 33.1 μg at/ℓ with the highest concentrations in lakes A-1, A-2, and B-2. Nitrate and phosphate concentrations were highest in the 3 Lakes B-1, C-1, and C-2.

The waters with high ammonia concentration, low nitrates and nitrites, and low dissolved oxygen tend to occur in lake areas with restricted winter water depths and high organics. Microbial oxidation of organic matter from summer production decreased winter dissolved oxygen concentrations while increasing ammonia in shallow lakes. Low dissolved oxygen levels, which were measured in the water column, and the lack of oxygen expected in the sediments allowed denitrification to proceed, reducing nitrate and nitrite concentrations (Keeney 1973). Where April 1980 (Table 5) dissolved oxygen concentrations were $\geqslant$ 2 mg/ℓ, nitrate plus nitrite concentrations were high (i.e. A-1, B-1, C-1, and C-2 with concentrations of approximately 4, 14, 10, and 30 μg at/ℓ, respectively). The dissolved oxygen was < 1 ml/ℓ in B-2, with a nitrate plus nitrite concentration of only 0.3 μg at/ℓ, while a high ammonia concentration of 25 μg at/ℓ was present.

Chlorophyll *a*

The chlorophyll *a* data collected during the summers of 1978 and 1979 are illustrated in 2 sets of 3 figures (Figures 50-55). Each figure contains the data from the 3 lakes in a lake study area.

The 1978 chlorophyll *a* profiles for the Northern Coastal Plain study lakes are illustrated in Figure 50. The horizontal axis has 2 sets of co-ordinates. The low range (0-5 mg/m^3) on the left describes the water column chlorophyll *a* profile values. The higher range (0-100 mg/m^2) on the right describes the benthic profile values. The vertical or depth axis denotes the sample depths, maximum recorded lake depth, and the depth at which the incident light level was 1% (1% light level).

The depth of occurrence of the 1% light level decreases in proportion to decreasing depth of lakes A-1, A-2, and A-3. This results from persistent winds that cause waves to continually resuspend bottom sediments in the shallow 1 to 2 m deep lakes. The 1% light level was below the greatest lake depth for A-1 and A-2 but was shown above the lake bottom for A-3. Water column chlorophyll *a* values in "A" lakes range from 0.1 to 1.3 mg/m^3. Values generally increase with depth within a lake and increase with decreasing maximum basin depth among the lakes. Both of these phenomena are probably due to the wave-generated resuspension and settling of benthic algae.

The benthic chlorophyll *a* values for "A" lakes are about an order of magnitude higher than the water column values. Benthic values range from 6.0 to 80.4 mg/m^2 and tend to increase with water depth. Benthic

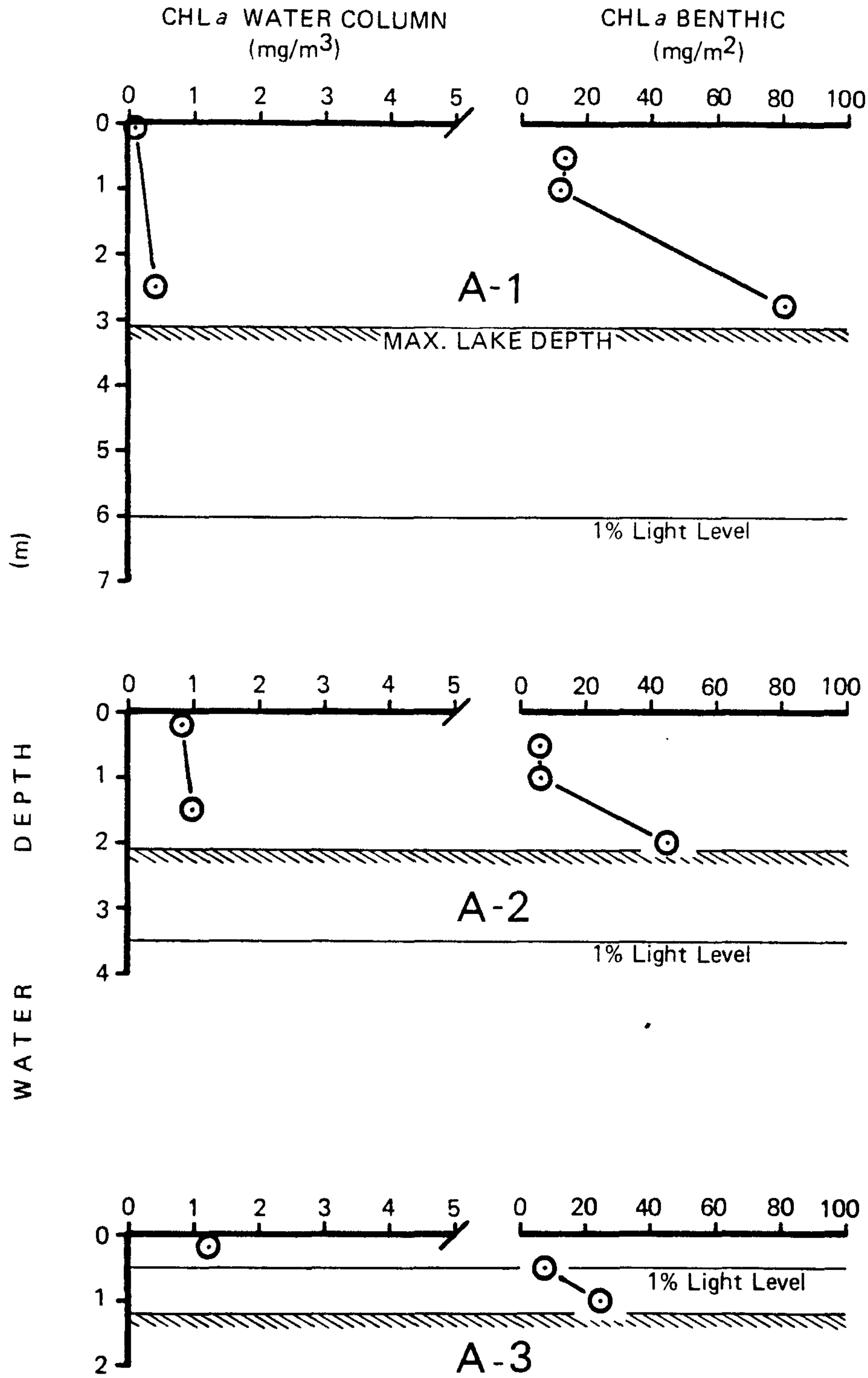


Fig. 50. Chlorophyll *a* profiles (water column and benthic) in Northern Coastal Plain lakes A-1, A-2, and A-3, 25 August 1978.

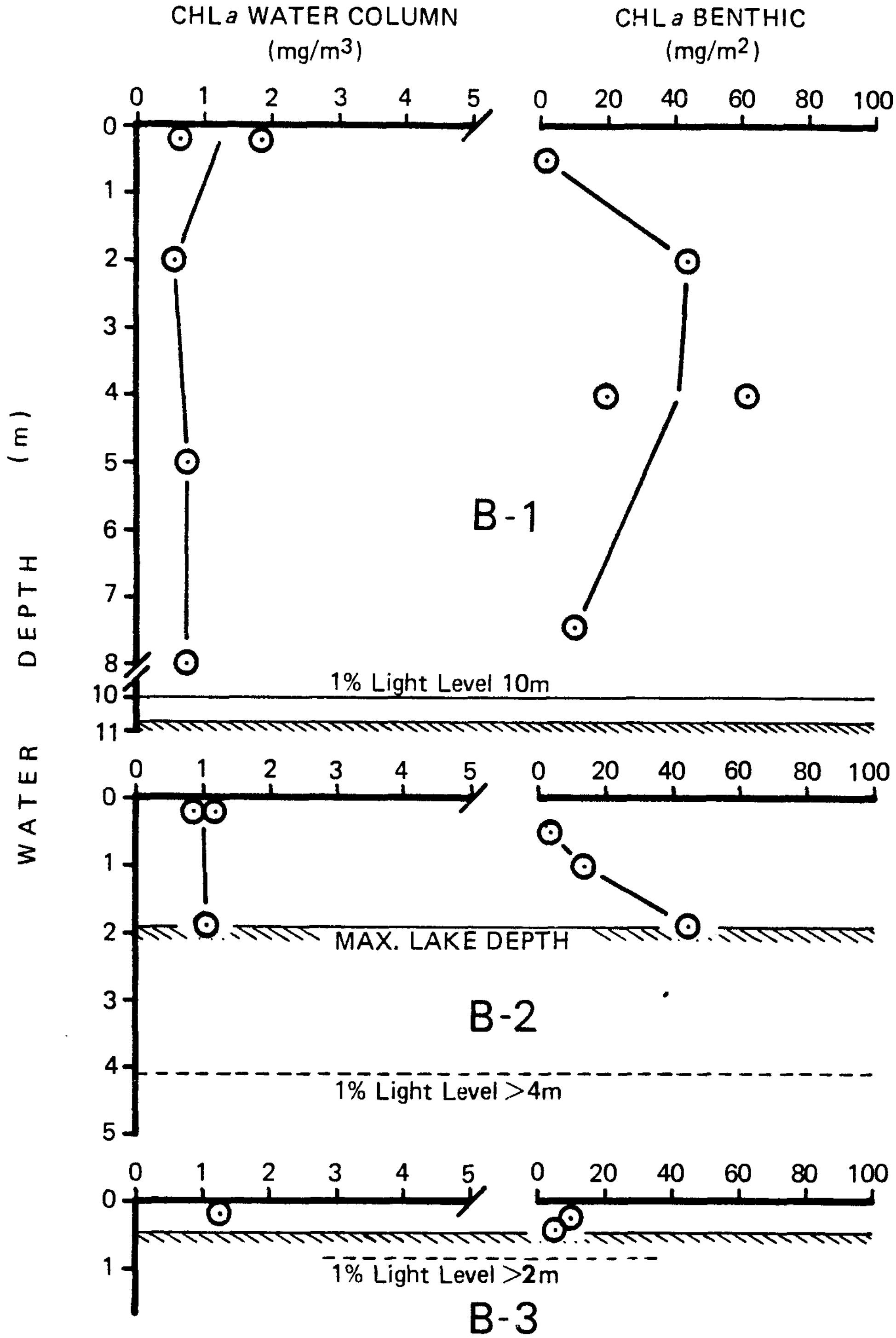


Fig. 51. Chlorophyll *a* profiles (water column and benthic) in Mid-Coastal Plain lakes B-1, B-2, and B-3, 23 August 1978.

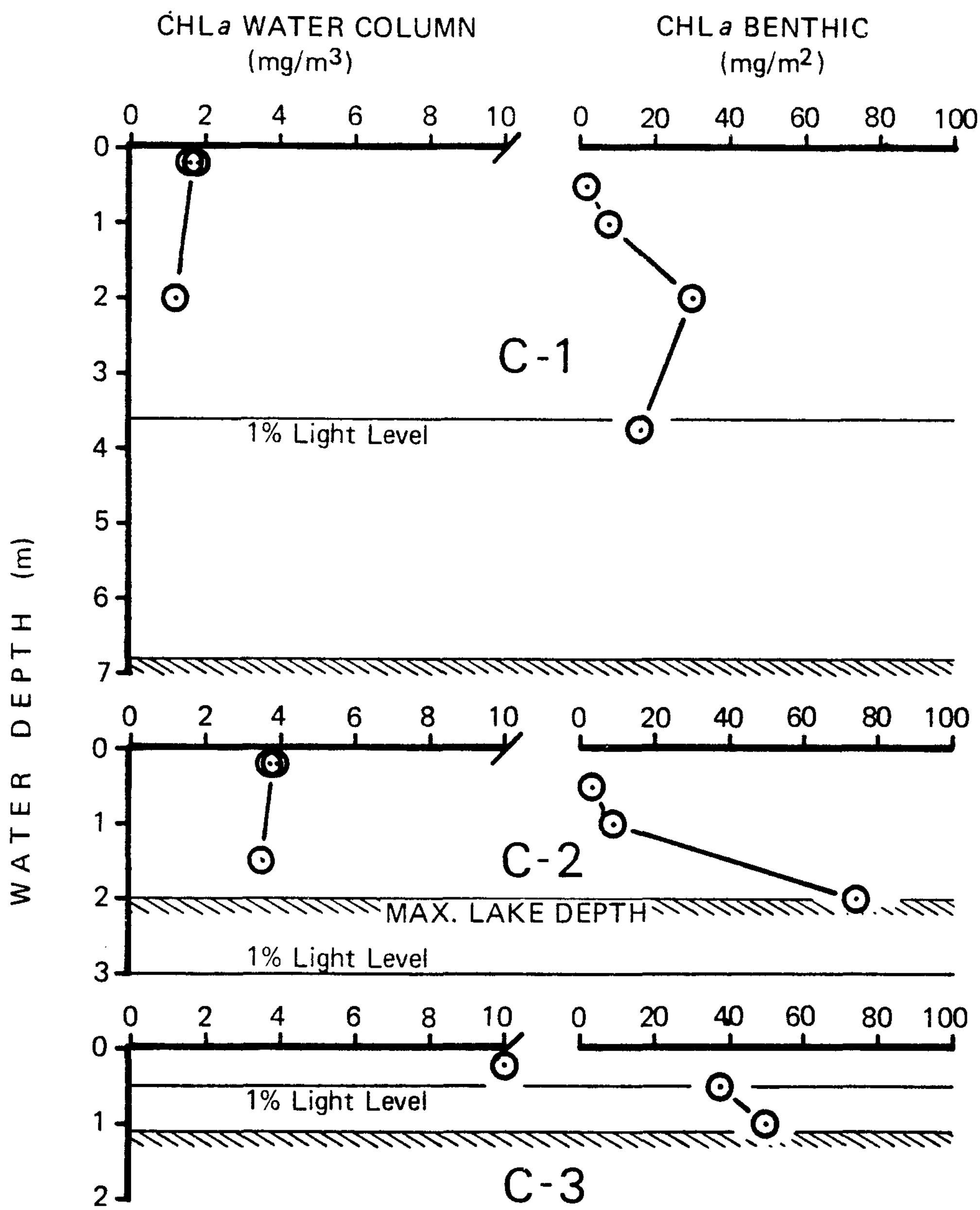


Fig. 52. Chlorophyll *a* profiles (water column and benthic) in Foothill lakes C-1, C-2, and C-3, 24 August 1978.

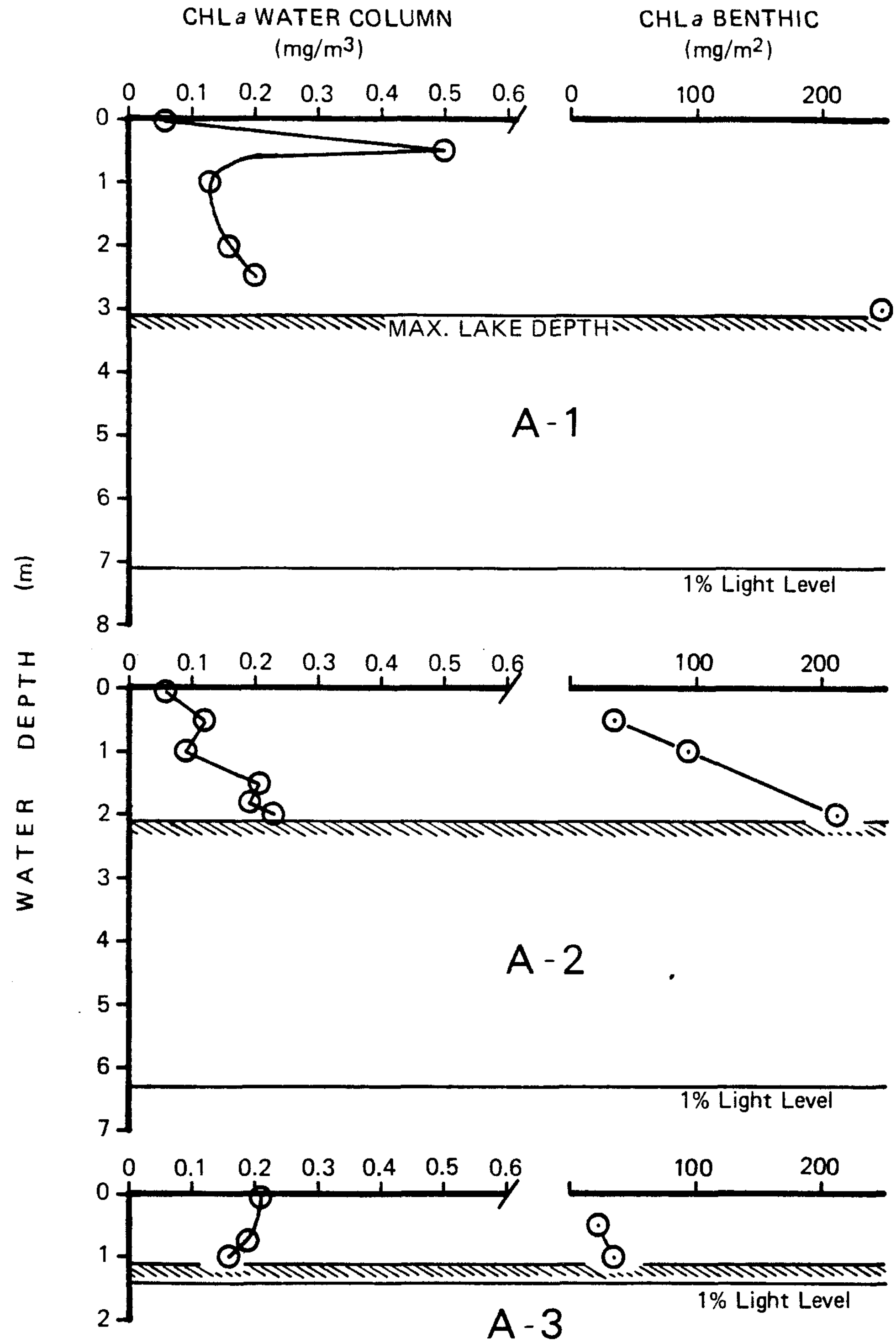


Fig. 53. Chlorophyll *a* profiles (water column and benthic) in Northern Coastal Plain lakes A-1, A-2, and A-3, 7-9 August 1979.

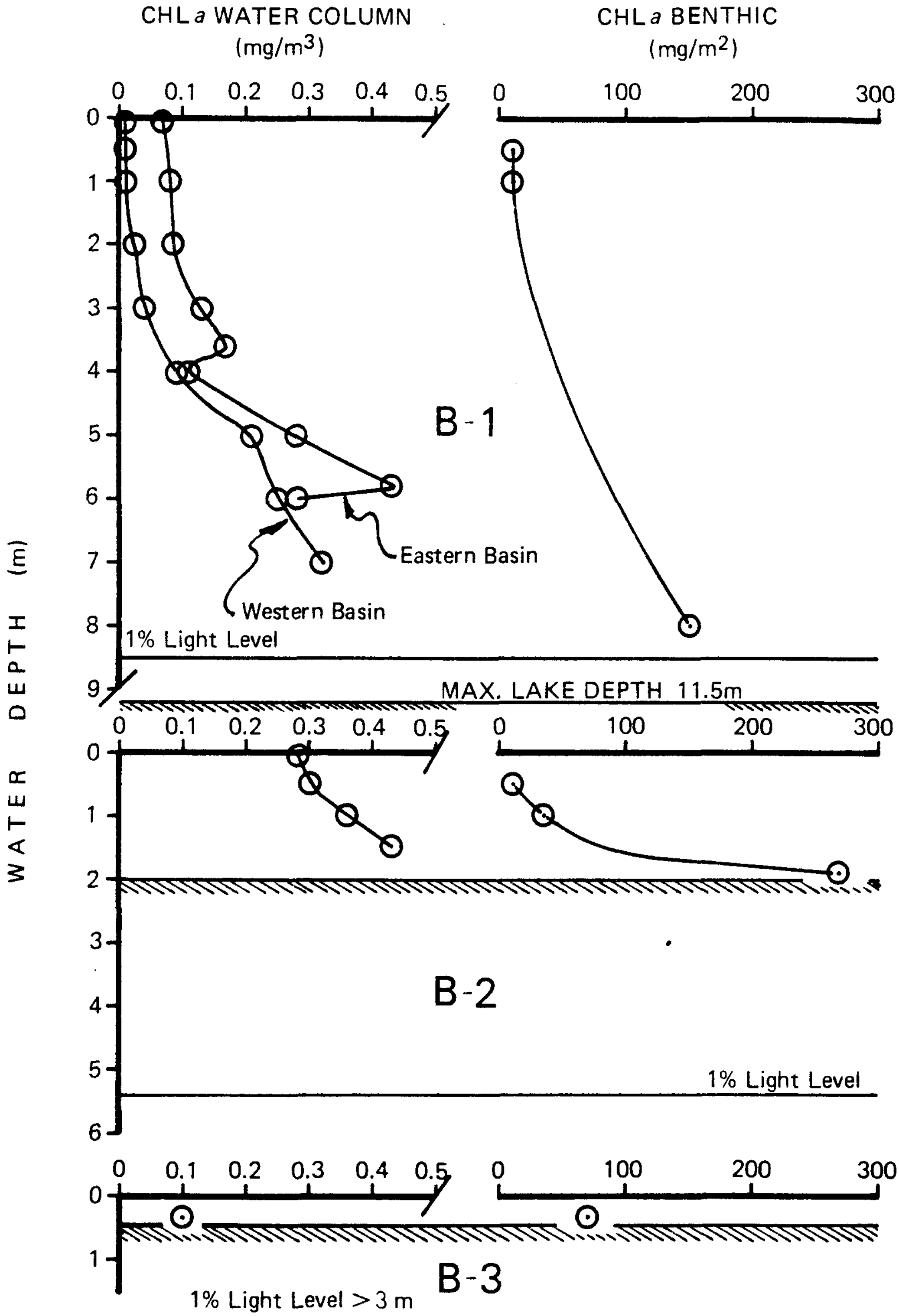


Fig. 54. Chlorophyll *a* profiles (water column and benthic) in Mid-Coastal Plain lakes B-1, B-2, and B-3, 8-9 August 1979.

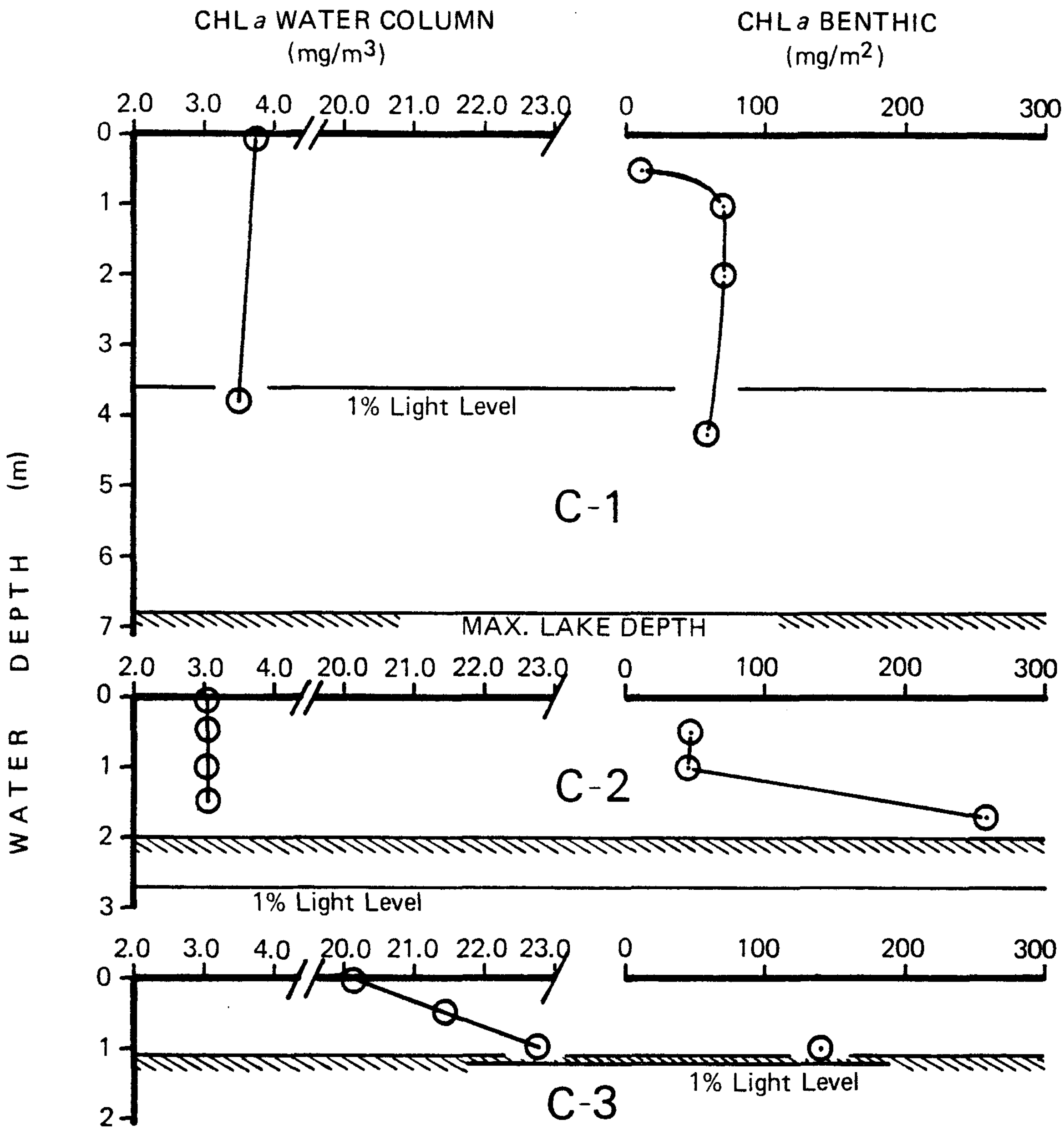


Fig. 55. Chlorophyll *a* profiles (water column and benthic) in Foothill lakes C-1, C-2, and C-3, 10-11 August 1979.

chlorophyll *a* values increase more dramatically in lakes A-1 and A-2, where the water is deeper and light attenuation is less. Resuspension of benthic plant matter from shallow areas and sufficient light for continued plant growth in deeper areas appear to be major factors. Benthic substrate composition also changes significantly in this zone of changing water depth and chlorophyll *a* values. Peat, gravel, and coarse sediments are found in shallow water along shore and grade into fine sediment offshore.

These 1978 chlorophyll *a* values take on a slightly different character in the "B" lakes (Figure 51). Winds were not as prevalent and light attenuation was less acute in Mid-Coastal Plain lakes than in Northern Coastal Plain lakes. The water column values do not vary as much (0.6 to 1.3 mg/m^3), but still tend to increase slightly in lakes of decreasing maximum depth. Benthic values ranged from 1.6 to 61.8 mg/m^2. Benthic values were low in the shallow areas that had coarse-grained substrate (sand). The fine sediments beyond the 1.0 m shelf break had benthic chlorophyll *a* values up to 61.8 mg/m^2. The reasons for the decrease in Lake B-1 benthic chlorophyll *a* below 2 m are not conclusive, but may be caused partly by greater amounts of algae settling in the mid-depth (1 m) benthic areas nearest the broad shallow shelves from which it was suspended, and also high primary production occurring in this mid-depth benthic zone. The 1% light level was at 10 m depth and should not have been a major limiting factor. Lake B-3 had a firm sandy bottom that had only slightly higher benthic values than did the shallow sandy shelves in lakes B-1 and B-2.

The Foothill Study Area C Lakes show many of the same general 1978 chlorophyll *a* trends (Figure 52) as were seen in the more northern lakes (Figures 50 and 51). The water column values are high in the shallow Lake C-3. Benthic values (1.3 to 73.3 mg/m^2) are almost an order of magnitude greater than water column values (1.2 to 10 mg/m^3). Benthic chlorophyll *a* increases with water depth within each lake except in C-1 where a slight decrease occurs at a depth slightly below the 1% light level. Both benthic and water column values tend to increase from C-1 to C-2 to C-3 or to increase with decreasing maximum basin depth.

Figures 53, 54, and 55 present a summer 1979 sequel to the summer 1978 chlorophyll *a* data just described. The methods used in acquiring the data differed (see Methods). Comparison of the 1978 with 1979 results shows that the same general trends occurred, but the range in the 1979 benthic versus water column chlorophyll *a* values was larger. The water column values are slightly less while benthic values are higher in the 1979 data. Some of the differences in absolute values between 1978 and 1979 data can be attributed to differences in methods and/or environmental conditions; however, the trends and relative differences within each data set appear to be consistent and assure the validity of both sets of measurements.

Water column chlorophyll *a* profiles ranged from 0.05 to 0.50 mg/m^3 for the Northern Coastal Plain Study Area A lakes (Figure 53). The 1979 water column values were in a similar range for all 3 lakes. The benthic values ranged from 20 to 250 mg/m^2. The benthic chlorophyll *a* was highest in Lake A-1 (250 mg/m^2), was less in Lake A-2 (40-210 mg/m^2), and was only 20-40 mg/m^2 in the shallowest Lake, A-3. The 1% light level exceeded the sampling depths at all "A" lake stations.

The Mid-Coastal Plain Study Area B lakes show much the same trend in the 1979 data (Figure 54) as they did in the 1978 data (Figure 51). The water column values are in a similar but more narrow range in all lakes and tend to increase with depth in lakes B-1 and B-2. Water column values ranged from 0 to 0.43 mg/m^3. Benthic chlorophyll *a* ranged from 10 to 270 mg/m^2. In lakes B-1 and B-2, benthic chlorophyll *a* increased as water depth increased. Unlike the smooth curve depicted in Figure 54, the function was probably more stair-stepped, changing with substrate type at the shelf break. The change undoubtedly occurs in lakes B-1 and B-2 at about 1 m, where the sandy terrace breaks off and grades into finer sediments in the deeper portions of the basins. The 1% light level exceeded the sampling depths at all "B" lake stations.

The 1979 Foothill Study Area C lake data (Figure 55) are similar to the 1978 data (Figure 52). The water column chlorophyll *a* ranged from 3 to 4 mg/m^3 in both lakes C-1 and C-2. Lake C-3 had a water column value of 10 mg/m^3 in 1978 and ranged from 20 to 23 mg/m^3 in 1979. Foothill "C" lake benthic values ranged from 10 to 260 mg/m^2 in 1979. Lake C-1 increased from 10 to 70 mg/m^2 at 1-2 m and declined to 60 mg/m^2 at 4.25 m, which was slightly below the 1% light level (3.6 m). Benthic chlorophyll *a* increased from 50 mg/m^2 at 0.5 m to 260 mg/m^2 at 1.7 m in the fine mid-basin sediments of C-2. Lake C-3 had a benthic value of 140 mg/m^2 at 1 m, which was near the 1% incident light level.

The following is a summary of the 1978 and 1979 chlorophyll *a* profile data illustrated in Figures 50 through 55. The benthic values are significantly greater than the water column values. In these shallow lakes the benthic chlorophyll *a* estimate of algal biomass far overshadows the estimate of water column plant biomass. The 1% incident light level shown for each lake was usually, but not always, below the maximum lake depth and rarely affected benthic or water column chlorophyll *a* values. Light may have been a limiting factor of observable significance in lakes A-3 (Figure 50) and C-1 (Figures 52 and 55). Water column values increased slightly as a function of decreasing maximum basin depth. This may be a result of wind generated waves mixing benthic algae into the water column.

Alexander et al. (1978) studied the effect of different suspended sediment loads on primary production and plant biomass in 2 deep arctic lakes (Peters and Schrader) in the Brooks Range, reporting benthic chlorophyll *a* values an order of magnitude greater than water column values. These results resemble those found in lakes C-1 and C-2. Alexander et al., suggest that should different light penetration exist in the same lake water, chlorophyll *a* benthic profiles will retain the same general shape and amplitude but be compressed in depth from less light penetration.

An interesting trend was noted when benthic data from all 9 study lakes were compared (Figures 50-55). The benthic values in the "A" lakes decrease in lake basins of decreasing maximum depth (A-1 to A-3). The benthic values are in a broad but similar range in the "B" lakes.

In "C" lakes the trend is for benthic values to decrease as maximum lake depths increase (C-3 to C-1). The benthic algae in shallow "A" lake basins may be removed from the benthic substrate by persistent wind-generated wave mixing. The opposite condition, benthic plant concentration in "C" lakes, may result from less wave mixing in all 3 "C" lakes with light attenuation restricting benthic plant biomass in the deeper C-1 basin.

Some of the trends discussed here may in part be controlled by lake factors other than depth and climate, but the 2 successive years of summer data show a relationship of algal biomass with water depth and climatic influence.

The horizontal distribution of chlorophyll *a* in the surface waters of study lakes was measured by acquiring at least 1 fluorometer transect in each lake. The measurements were taken on 9 and 11 August 1979, and are illustrated in Figures 56, 57 and 58. Chlorophyll *a* values ranged from less than 0.01 mg/m^3 to more than 24 mg/m^3 in the surface water of the study lakes.

Chlorophyll *a* values ranged from less than 0.01 to 5.05 mg/m^3 in the Northern Coastal Plain Study Area A lakes. Kangas (1972) measured chlorophyll *a* in the water column of 17 Northern Coastal Plain ponds. He recorded a range of 0.3 to 37 mg/m^3 and reported that the "values were much higher than previously reported in the literature". Kalff and Welch (1974) reported August 1972 values ranging from 0.05 to 0.85 mg/m^3 in Char Lake, an ultraoligotrophic arctic lake in Canadian Northwest Territories. Lake A-1 had low values of 0.02 mg/m^3 across

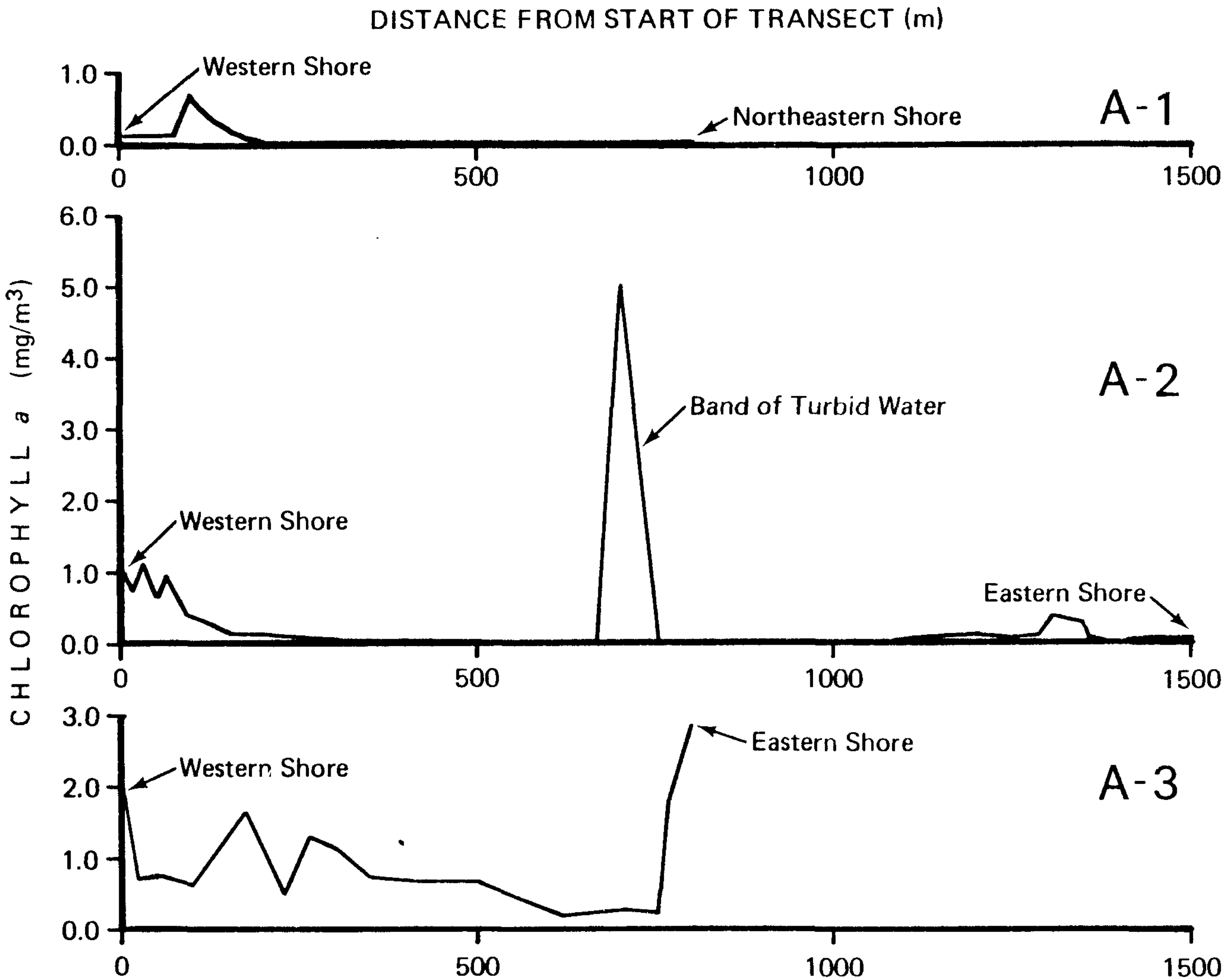


Fig. 56. Chlorophyll *a* from continuous surface water fluorometer transects on Northern Coastal Plain lakes A-1, A-2, and A-3, 9 August 1979.

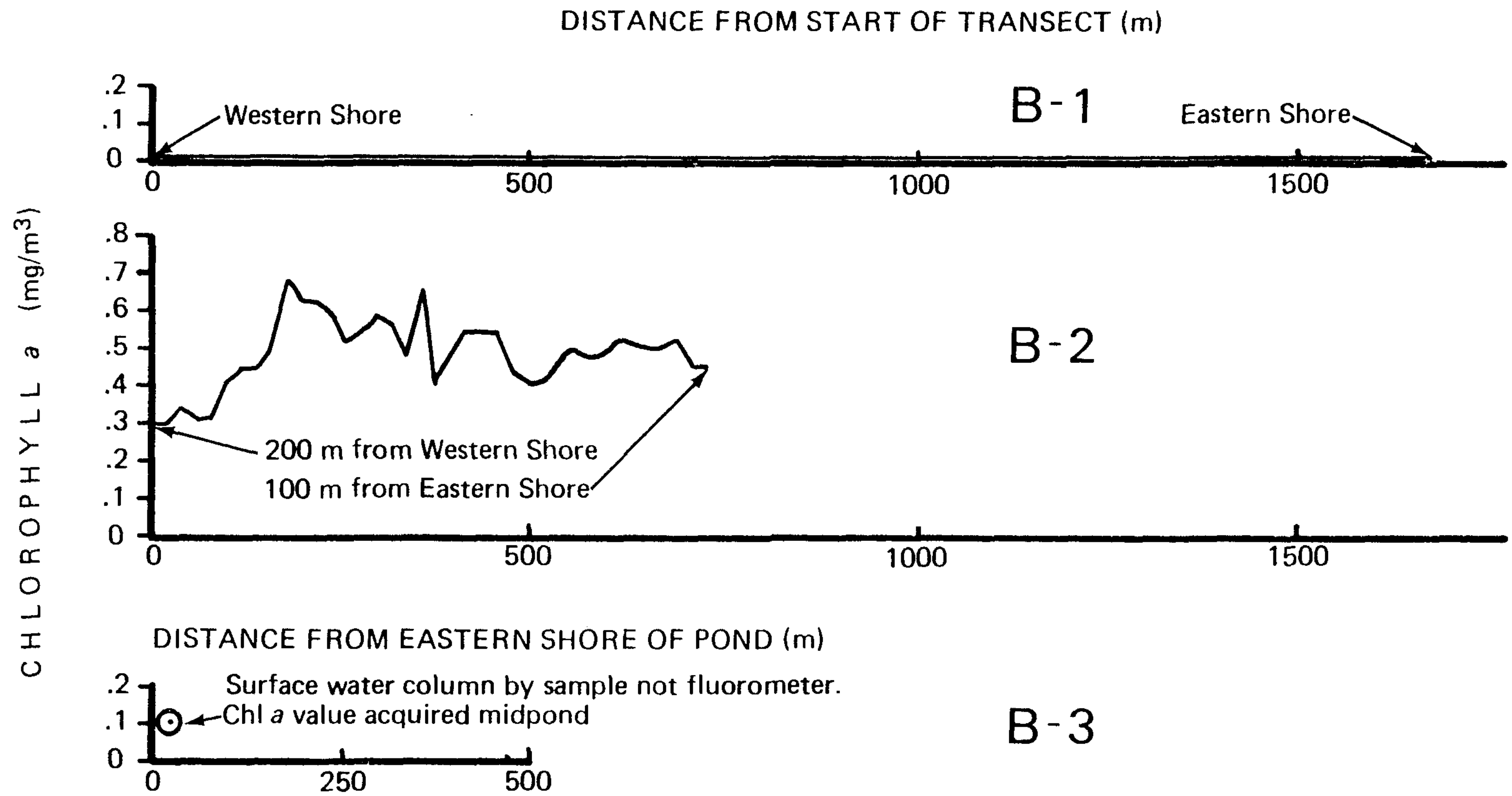


Fig. 57. Chlorophyll *a* from continuous surface water fluorometer transects on Mid-Coastal Plain lakes B-1 and B-2 and a single sample from Pond B-3, 9 August 1979.

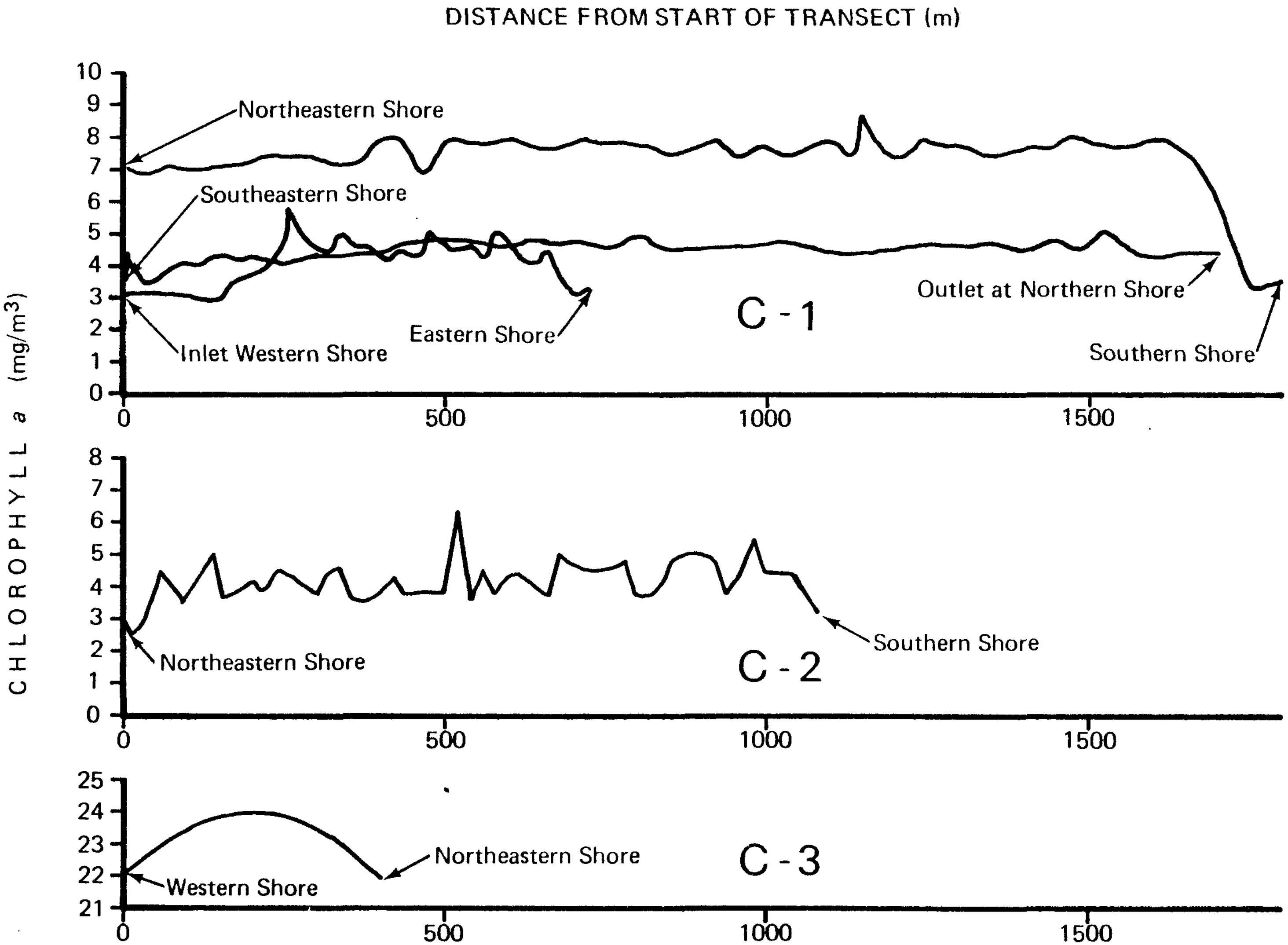


Fig. 58. Chlorophyll *a* from continuous surface water fluorometer transects on Foothill lakes C-1, C-2, and C-3, 11 August 1979.

most of the lake, with a peak of 0.67 mg/m^3 near the western shore (Figure 56). The peak near the western shore undoubtedly resulted from wind-generated waves mixing benthic algae into the water column. The prevailing winds are from the east, causing wave activity to be heaviest on the western shore.

The chlorophyll *a* transect on Lake A-2 had 3 peaks and a range of values from less than 0.01 mg/m^3 to 5.05 mg/m^3 (Figure 56). The large peak of 5.05 mg/m^3 occurred mid-lake in a band of turbid water that was visible from the floatplane during the fluorometer transect sampling. Although the plume was mid-lake, it was generated initially by wave activity on shore and was drifting and diffusing offshore. The second largest peak (1.1 mg/m^3) occurred on the western shore, where wave activity was heaviest. A small peak of 0.4 mg/m^3 was 200 m from the eastern shore. As with A-1, the peaks in A-2 indicate that wave activity mixed benthic algae into the surface water.

Lake A-3 had a higher chlorophyll *a* concentration across the entire transect than the other "A" lakes. The values range from 0.2 to 2.8 mg/m^3 (Figure 56). The highest values measured were 2.0 and 2.8 mg/m^3, recorded near the western and eastern shores, respectively. The values averaged about 0.5 mg/m^3 across the entire basin. The shallow lake depth (1.0 m) permitted benthic algae to be mixed into the water column across the entire basin. The surface waters of the Study Area A lakes might have had smaller chlorophyll *a* concentrations were it not for persistent winds, shallow basin depths, and high benthic plant biomass.

The Mid-Coastal Plain Study Area B lakes had little wind while the fluorometer transects were being made. Chlorophyll *a* ranged from less than 0.01 to 0.68 mg/m^3 (Figure 57). Lake B-1 had so little chlorophyll *a* that it could not be measured ($\leqslant$ .01 mg/m^3). Lake B-2 chlorophyll *a* averaged around 0.5 mg/m^3 and ranged from 0.28 to 0.68 mg/m^3. The largest B-2 values occurred mid-lake. Pond B-3 was too small to permit acquisition of a fluorometer transect. A single surface-water sample was analyzed and contained 0.10 mg/m^3 chlorophyll *a*. The surface water of the "B" lakes had little entrained plant biomass and little potential for suspension of benthic algae because the air was calm.

The chlorophyll *a* content of Foothill Study Area C lake surface waters was the highest of all the lake study areas. Values ranged from 2.5 to 24.0 mg/m^3 (Figure 58) in these lakes that were noticeably brown from high humic content. Suspension of benthic algae was of less consequence in "C" lakes than with "A" lakes.

Three chlorophyll *a* fluorometer transects were acquired on Lake C-1 (Figure 58). Values from two of these transects were similar, averaging about 4.4 mg/m^3. A third transect was acquired immediately after a brief rain and wind squall that approached from the south. The squall created white caps across the entire lake except on the southern shore where fetch was insufficient to produce large waves. The chlorophyll *a* values increased to more than 7 mg/m^3 across the basin and decreased abruptly to 3 mg/m^3 near the southern shore where wave activity was less. The increase in surface water plant biomass resulted from the mixing of a subsurface concentration that existed within the wave-mixed layer, possibly from shoals such as knolls or a nearshore terrace.

Lake C-2 chlorophyll *a* values ranged from 2.5 to 6.4 mg/m^3 (Figure 58). The lowest values were near shore, and mid-lake values averaged 4 mg/m^3. The air was calm.

Lake C-3 had the highest recorded surface water chlorophyll *a*. The range was from 22.1 mg/m^3 near shore to 24 mg/m^3 mid-lake. The air was calm. The chlorophyll *a* values tended to be lower near shore than mid-lake in all "C" lakes.

The benthic algae are wind/wave mixed into the water column more often in the shallow portions of a lake than in deeper mid-lake areas. This concentrates plant biomass in deeper areas within a lake basin. Substrate grain size is also sorted by wave action in shoal areas. Figures 50 to 55 illustrate that the shallow margins of lakes have a lower benthic algae biomass than do the deeper portions. Lakes with a shallow basin throughout have more uniform plant biomass over the entire lake bottom. Lake basins with deep centers have large ranges of benthic chlorophyll *a*, with high concentrations in the deeper areas and small concentrations on the shallow margins.

The surface water values are strongly influenced by a combination of basin depth and wind-generated wave activity. The "A" lakes are affected most significantly, because they are shallow and have persistent winds. The "C" lakes had intrinsically higher chlorophyll *a* in the water column than did "A" or "B" lakes, but wind was not a major factor in the production of chlorophyll *a* peaks in "C" lake surface waters.

The "B" lakes had the lowest surface water plant biomass. They had little intrinsic water column chlorophyll *a* and no wind mixing of benthic algae to supplement the surface water concentrations measured.

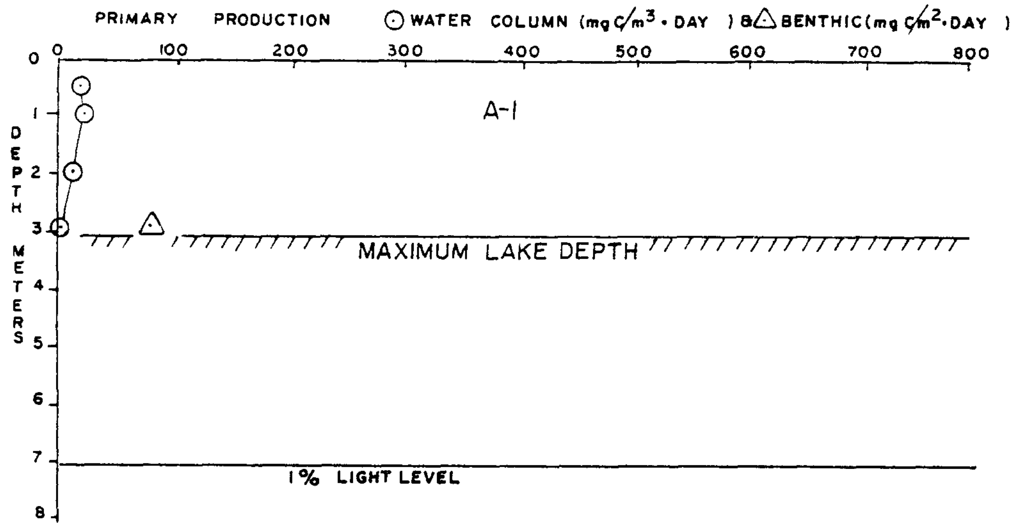
Water column chlorophyll *a* measured by both fluorometer transects and vertical profiles ranged from less than 0.01 to 24.05 mg/m^3 in the 9 study lakes. Gross estimates of benthic chlorophyll *a* ranged from 1.3 to 270 mg/m^2 for the same 9 lakes.

Spring phytoplankton biomass estimates were not much different from the summer ones. Ice covered lakes A-1, B-2, and B-1 had higher chlorophyll *a* values than were recorded during the summer. Values ranged from 17.9 to 1.2 mg/m^3, respectively (Table 5). The values for A-2, C-1, and C-2 were about the same as or slightly lower than summer values.

No significant depth or climatic relationships were observed in the few spring measurements; however, summer chlorophyll *a* measurements were obviously correlated with both water depth and climatic gradient along the study transect.

Primary Production

Water column and benthic primary production (PP) profile measurements acquired for the 9 study lakes are shown in Figures 59, 60 and 61. The 3 lakes within each study area are illustrated in a single figure, with the maximum depth of the lakes and 1% incident light level illustrated in the same manner used in the chlorophyll *a* profiles figures.



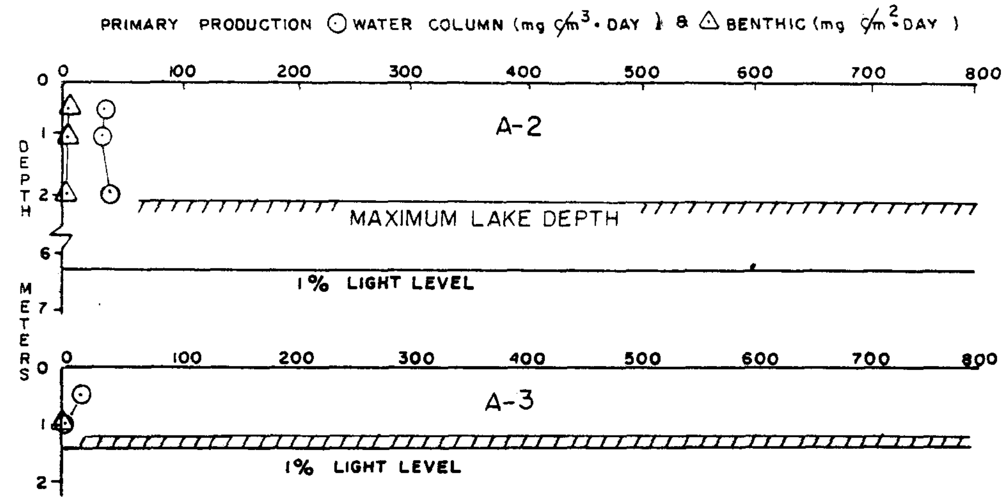


Fig. 59. Water column and benthic ^{14}C primary production in Northern Coastal Plain lakes A-1, A-2, and A-3, 7-11 August 1979.

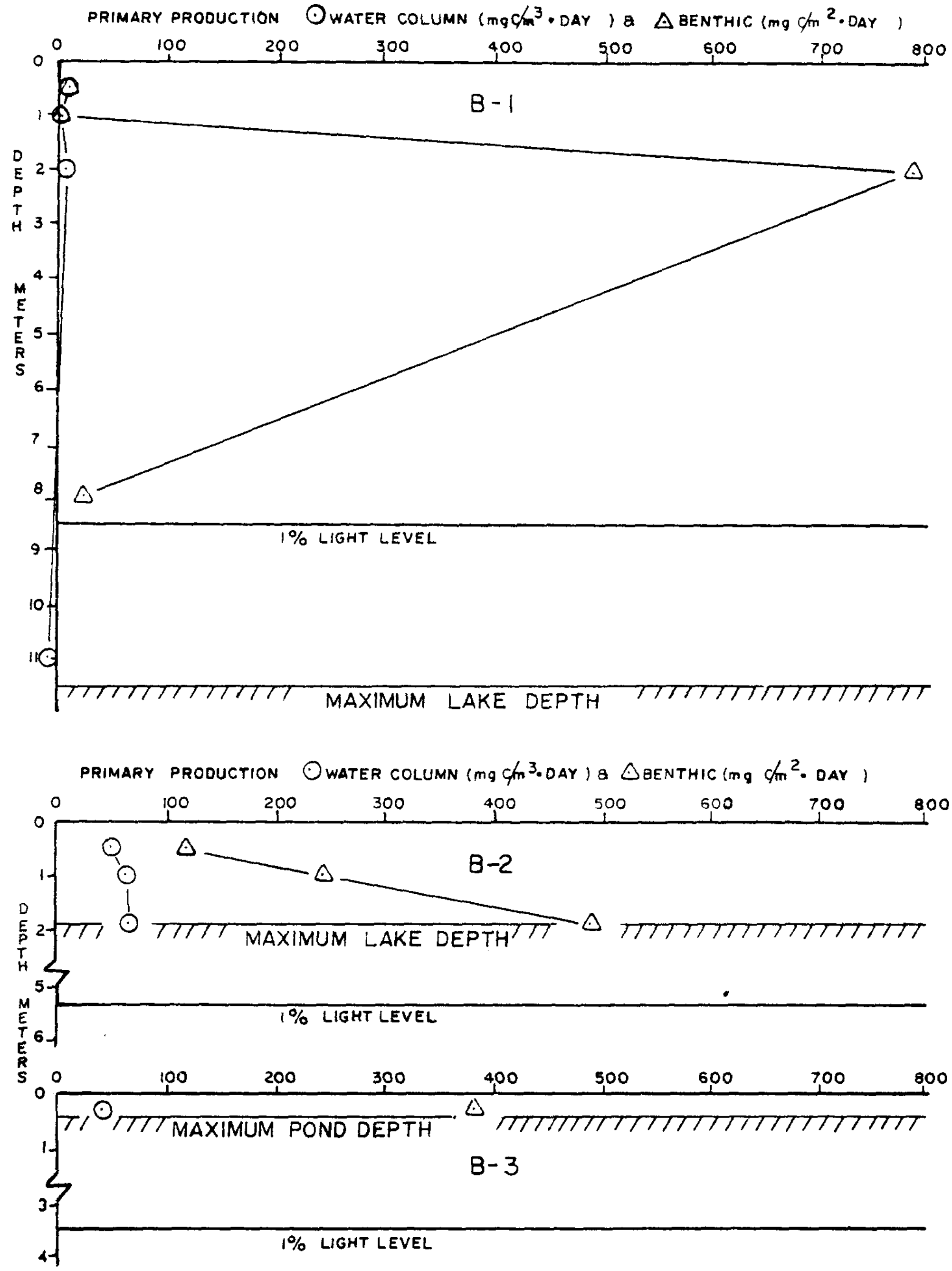
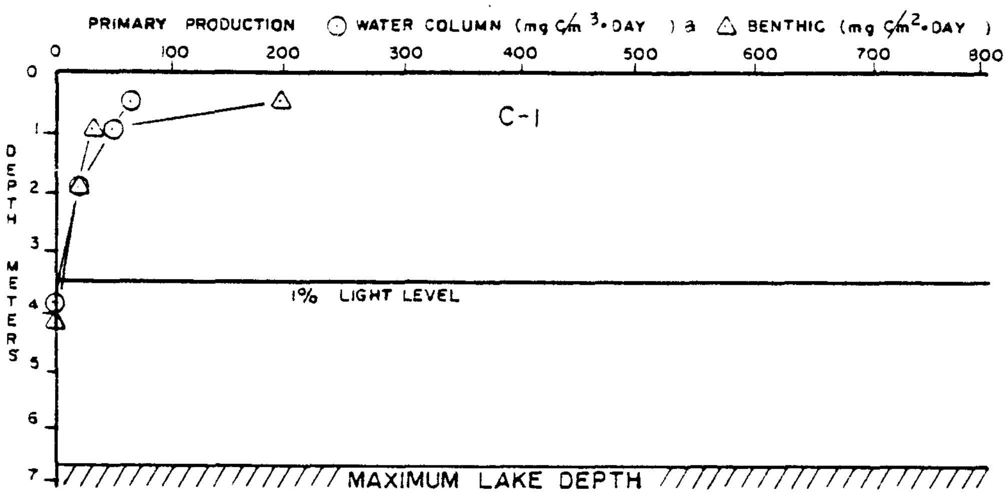


Fig. 60. Water column and benthic ^{14}C primary production in Mid-Coastal Plain lakes B-1, B-2, and B-3, 7-11 August 1979.



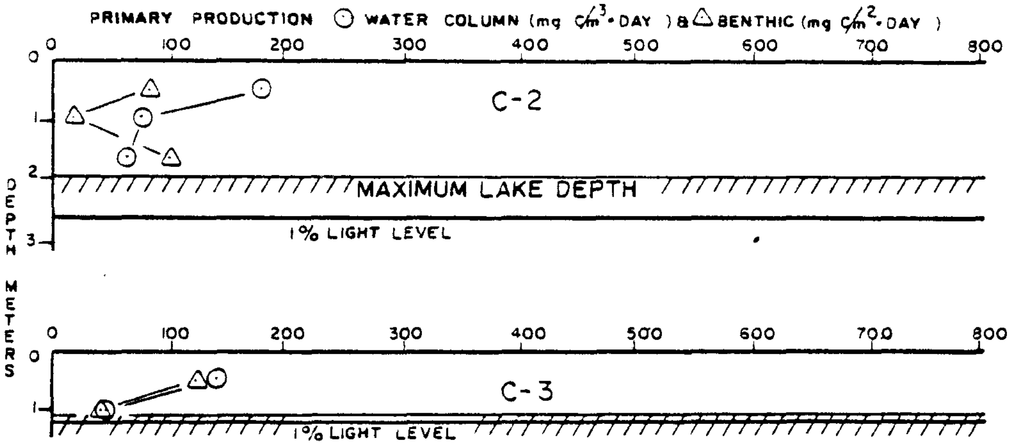


Fig. 61. Water column and benthic ^{14}C primary production in Foothill lakes C-1, C-2, and C-3, 7-11 August 1979.

The PP profiles for Northern Coastal Plain Study Area A lakes are illustrated in Figure 59. At this latitude, water column values ranged from 3 to 40 mg C/m^3·day compared with benthic values of 1 to 84 mg C/m^3·day. The 1% incident light level was at a depth greater than maximum lake depth in all 3 lakes.

In Lake A-1, the deepest lake, the 1 benthic PP measurement obtained was 84 mg C/m^2·day at 3 m depth. Water column values ranged from 3 to 23 mg C/m^3·day. Alkalinity (52.6 mg/ℓ), pH (7.41), and dissolved inorganic carbon (13.9 mg/ℓ) were high in A-1.

The benthic PP profile in A-2 was less than the water column profile. Benthic PP ranged from 5 to 8 mg C/m^2·day. Water column PP ranged from 37 to 43 mg C/m^3·day.

In the shallowest lake, A-3, the benthic PP value was also less than the water column PP. The benthic PP was 1 mg C/m^2·day. The water column PP ranged from 17 mg C/m^3·day at 0.5 m to 3 mg C/m^3·day at 1.0 m water depth. Wave action and large amounts of suspended matter may have caused reduced PP at the 1 m maximum lake depth.

The PP profiles for Mid-Coastal Plain Study Area B lakes are illustrated in Figure 60. The benthic PP values far exceeded the water column values in the "B" lakes. Benthic PP ranged from 5 to 788 mg C/m^2·day. The water column PP values ranged from -7 to 65 mg C/m^3·day. The 1% incident light level was above maximum lake depth on only B-1 at 8.5 m. In the study lakes, alkalinity was highest for "B" lakes ranging from 12.7 mg/ℓ in B-3 to 69.4 mg/ℓ in B-1. Alkalinity (69.4 mg/ℓ) and dissolved inorganic carbon (17.8 mg/ℓ) were particularly high for B-1.

Lake B-1 had almost insignificant water column PP, ranging from -7 to 11 mg $C/m^3 \cdot day$. Benthic PP ranged from 5 mg $C/m^2 \cdot day$ at 1 m to 788 mg $C/m^2 \cdot day$ at 2 m water depth. The major discontinuities between these 2 benthic stations in B-1 was water depth and sediment type. The 1 m station had hard packed white sand. The 2 m benthic PP station had fine, soft sediment or mud. The benthic PP was reduced to 24 mg $C/m^2 \cdot day$ at the 8 m station near the 1% incident light level. A slightly negative water column value (-7 mg $C/m^3 \cdot day$) was calculated for the 11 m depth, which was below the 1% incident light level.

The 1% incident light level for Lake B-2 and Pond B-3 were below maximum basin depths. Lake B-2 benthic PP continued to increase with depth from 120 mg $C/m^2 \cdot day$ at 0.5 m to 493 mg $C/m^2 \cdot day$ at 2 m. The water column PP also increased slightly with depth from 51 mg $C/m^3 \cdot day$ at 0.5 m to 65 mg $C/m^3 \cdot day$ at 2 m. Finally, the 2 PP measures in Pond B-3 were 385 mg $C/m^2 \cdot day$ benthic PP and 85 mg $C/m^3 \cdot day$ for the water column.

The PP profiles for Foothill Study Area C lakes are illustrated in Figure 61. Profiles of benthic and water column PP values were surprisingly parallel in all 3 lakes. Benthic PP ranged from 2 to 196 mg $C/m^2 \cdot day$. Water column PP ranged from 3 to 180 mg $C/m^3 \cdot day$. The lowest benthic and water column PP values were sampled at 4 m in C-1, where a 1% incident light level occurred at 3.5 m water depth.

Lake C-1 benthic PP ranged from 2 mg $C/m^2 \cdot day$ at 4 m to 196 mg $C/m^2 \cdot day$ at 0.5 m. Water column PP ranged from 3 mg $C/m^3 \cdot day$ at 4 m to 67 mg $C/m^3 \cdot day$ at 0.5 m.

Lake C-2 benthic PP ranged from 20 to 103 mg C/m^2·day. Water column PP ranged from 64 to 180 mg C/m^3·day.

Lake C-3 benthic and water column PP profiles were similar. Benthic PP ranged from 41 mg C/m^2·day at 1 m to 125 mg C/m^2·day at 0.5 m. Water column values ranged from 46 mg C/m^3·day at 1 m to 142 mg C/m^3·day at 0.5 m.

Rates of arctic lake and pond primary production have been studied by a number of investigators (Hobbie 1962 and 1972, Kalff 1970, Howard and Prescott 1971, Stanley 1972, 1974, 1976a, 1976b and 1976c, McCart et al. 1974, Welch and Kalff 1974, Kalff and Welch 1974, Alexander et al. 1978, Hobbie 1980). A variety of results has been reported for production rates. All investigators have found that primary production decreases in the winter to very low or undetectable rates of production. Summer water column primary production estimates range from 3 to 300 mg C/m^3·day. Howard and Prescott found that shallow (1 m) ponds may have high production rates (223-285 mg C/m^3·day), while most lakes (> 1 m) had a mean rate of 20-44 mg C/m^3·day.

Brylinsky and Mann (1973) concluded from International Biological Program lake studies that morphology of lake basins on a global scale has little influence on primary productivity per unit area. This means that lakes with similar nutrient and energy input and like surface areas should have the same phytoplankton production, whether they are shallow or deep. According to their theory, a shallow lake would have more concentrated phytoplankton per unit volume than a deep lake. But Frey and Stahl (1958) found that morphometry of high-latitude lake basins does control rate of production, with shallow lakes having a higher intensity of primary production than deeper lakes. Benthic rates of primary production (m^2) are higher than water column (m^3) and contribute significantly to total lake basin productivity, especially in shallow thaw lakes where enough light energy can reach the lake bottom for photosynthesis (Stanley 1972, Welch and Kalff 1974, Alexander et al. 1978). Welch and Kalff found that 80% of Char Lake's (lat. 74°72'N) photosynthesis was benthic. Northern lakes have relatively low efficiency of light utilization compared with southern lakes. This is due in part to photoinhibition of phytoplankton photosynthesis and/or to the low nutrient loading. Schindler (1978) stated that,

> "There is some evidence for a correlation between latitude and nutrient input and it is possible that this may explain the good correlation between latitude and production observed by earlier investigators."

Bunnell et al. (1975) stated that an outstanding feature of the arctic tundra, particularly the wet coastal ecosystem, is the large amount of energy bound up in dead organic matter. There is little accumulation or turnover of energy above ground. Instead, above-ground portions of sedges and grasses grow and die each summer, adding to the below-ground biomass. Dead organic matter can be 50 to 400 times the annual net primary production. Low rates of decomposition and nutrient release hamper energy flow.

Terrestrial and aquatic systems appear to have a closely tied energy budget with accumulation of organic matter in the terrestrial habitat and degradation in freshwater (Bunnell et al. 1975). Tundra thaw ponds show a deficit in production relative to decomposition. The arctic wetland energy budget is tied to and dependent upon terrestrial and migratory faunal (bird and mammal) energy flow. Lakes and ponds frequented by birds and mammals have potential for higher rates of production than others because their nutrient turnover rate is more rapid. The greater the lake productivity (vegetation, invertebrates, and/or fish) the more likely that habitat is to continually attract fauna and increase nutrient turnover rates.

Photosynthesis in shallow ponds that freeze solid is limited to the 3 to 4 month, ice-free period of the year; however, benthic PP in shallow ponds was calculated to be from 4 to 10 g $C/m^2 \cdot$year by Stanley (1976a). In contrast, Stanley found that benthic PP was lower (2.3 g $C/m^2 \cdot$year) in Lake A-2 due to lower light intensities at the sediment surface, lower water temperatures, and shorter ice-free periods than in ponds. Hobbie (1972) presented annual production data on benthic algae (14 g $C/m^2 \cdot$year) and macrophytes (15 g $C/m^2 \cdot$year) that were each about 15 times the phytoplankton production (0.4 to 1.0 g $C/m^2 \cdot$year) in a tundra pond located in Study Area A. He also reported phytoplankton production in a deep arctic lake to be 0.9 to 7.5 g $C/m^2 \cdot$ year. This larger water column production does not compensate for the benthic production in a tundra pond. The average annual production in shallow or deep arctic water basins is at most a fraction of the average production in temperate lakes.

Primary production investigations by Stanley (1974) show summer benthic PP declined appreciably during August 1971 in Northern Coastal

Plain lakes and ponds. Lake A-2 went from 62 to 52 mg $C/m^2 \cdot day$ benthic PP. Some ponds in the Barrow vicinity went from about 240 to 72 mg $C/m^2 \cdot day$. Benthic algae biomasses in the ponds studied by Stanley reached peak production at the end of July or early August 1971. Primary production measurements were acquired during this study from 7 to 11 August 1979. The values reported are undoubtedly lower than spring and early summer maximums, but serve to illustrate the relative differences in study lakes during the mid-August 1979.

Stanley (1974) found Lake A-2, with a maximum depth of 2 m, to have equally productive phytoplankton and benthic algae, but benthic algae dominated his shallow tundra ponds by an order of magnitude. Stanley also noted that despite the great differences in the relative importance of plankton and benthic algae in deep lakes versus shallow lakes and ponds, all have approximately the same cumulative annual production. His results indicate that lake depth is likely to have little effect on total algal biomass produced. Rather, depth determines relative amounts of solar energy converted to phytoplankton versus benthic algae.

Howard and Prescott (1971) studied seasonal variation of water column PP in Lake A-1, Lake A-2, and Malikpuk Lake near Barrow and found that peaks of high and low PP varied by an order of magnitude with time. The peaks did not coexist in time in neighboring lakes. Therefore, one might expect one lake to have high PP while an adjacent one was low. Primary production often has a delayed response to addition of a limiting substrate. Water column PP values reported by Howard and Prescott (1971) ranged from 5 to 55 mg $C/m^3 \cdot day$, 15 to 80 mg $C/m^3 \cdot$

day, and 50 to 300 mg $C/m^3 \cdot day$ for A-1, A-2, and Malikpuk Lakes, respectively. The data acquired during this study are from a specific time and provide no temporal perspective.

The PP values illustrated in Figures 59, 60, and 61 were used with planimetered depth contours from the 9 lakes figures to calculate total lake basin primary production (Table 6). The surface area of each lake was used to reduce the total lake water and benthic PP to average primary production per square meter of integrated water column and substrate. Table 6 lists these calculated values, plus maximum benthic and water column chlorophyll *a* and 1% incident light level for each of the 9 study lakes.

In the Northern Coastal Plain Study Area A lakes, the average combined water column and benthic PP varied from 122, 64, and 12 mg $C/m^2 \cdot day$ for A-1, A-2, and A-3, respectively (Table 6). Water column PP contributed more than 90% of the total PP in the shallow lakes, A-3 and A-2, and only 31% of the total in A-1. This was the opposite of what the previous discussion suggests, because the shallow lakes have a greater potential for benthic PP. One explanation for these results might be the wind-driven waves that persisted while the lakes were being sampled. The large sediment plume noted in A-2 during sampling and the 1.4 m 1% incident light level recorded in A-3 suggest that waves were removing benthic algae from the lake bottom and consequently light penetration to the lake substrate was reduced. The lake with highest light attenuation (A-3) had the least benthic PP per m^2.

Table 6. Primary production for study lakes sampled 7-11 Aug. 79.

Lake Description					Total Lake Basin Primary Production (PP) (mgC/day x 10^6)					Average Primary Production per meter^2 (mgC/m^2·day^1)		
			Chl *a* maximum									
Lake No.	Max. Depth (m)	1% Incident Light Level (m)	Water Column (mg/m^3)	Benthic (mg/m^2)	Water Column	Benthic	Total	% PP Water Column	% PP Benthic	Integrated Water Column	Benthic	Total
A-1	3.1	7.1	.67	250	23	51	74	31	69	38	84	122
A-2	2.1	6.3	5.05	210	296	31	327	91	9	58	6	64
A-3	1.2	1.4	2.83	40	14	1	15	93	7	11	1	12
B-1	11.5	8.5	.43	150	41	597	638	6	94	19	275	294
B-2	1.9	5.4	.68	270	52	264	316	16	84	49	248	297
B-3	.45	3.0	.10	70	0.15	4	4.15	4	96	15	385	400
C-1	6.8	3.6	8.70	60	130	41	171	76	24	95	30	125
C-2	2.0	2.7	6.37	260	129	59	188	69	31	169	77	245
C-3	1.1	1.2	24.05	140	8	9	17	47	53	84	90	174

In the Mid-Coastal Plain Study Area B lakes light attenuation was low. Benthic PP was approximately an order of magnitude greater than water column PP in all "B" lakes. The average PP for both benthic and water column in "B" lakes ranged from 294 to 400 mg C/m^2·day, which was larger than that calculated for any "A" or "C" lake (Table 6). High benthic productivity was not directly correlated with high benthic algal biomass (chlorophyll *a*), but both were assisted by low light attenuation. Calm air conditions left the substrate undisturbed and allowed maximum penetration of light for efficient benthic PP.

In the Foothill Study Area C lakes the average PP ranged from 125 to 245 mg C/m^2·day (Table 6). The relative contribution of benthic to water column PP increased with decreasing maximum lake depth. The deep C-1 lake had a 76% water column and a 24% benthic PP, or a 3 to 1 ratio. The ratio in Lake C-2 was 2 to 1, and 1 to 1 for the shallow Lake C-3. In Lake C-1 discrete benthic and water column PP values were about equal (Figure 61), but because Lake C-1 had a deep water column throughout which PP occurs, the integrated water column PP calculated was 3 times greater than benthic PP. Less water depth in C-3 provided less integrated total water column PP (Table 6) even though the sampled water column PP per m^3 was greater (Figure 61).

Water depth and climatic gradient significantly affected the PP of the lakes studied, but evidence from literature and the results of the study suggest that the combined annual benthic and water column PP is not related to lake depth alone. A combination of climatic gradient conditions (i.e. wind and resulting light attenuation from suspended sediment loads and incident solar radiation) and individual lake conditions (basin morphology, sediment and water column temperatures, benthic substrate, and alkalinity) affect primary production in these lakes. Although correlations between PP and variations in nutrients and/or consumers were not obvious in this study, nutrients and light attenuation by suspended matter are prime factors limiting overall PP in these oligotrophic lake systems.

Emergent Vascular Vegetation

One vegetation transect was examined within each study lake in an area containing maximum emergent vegetation. Plant species were identified, plant densities and water depths were measured, and substrate types were recorded. The vegetation identified in a transect does not necessarily represent all emergents within the lake basin.

Table 7 is a list of species found in the study lakes. This table is not an all-inclusive species list, but instead lists those plants encountered in the lake transect areas visited. Ten species of plants were identified in the 9 study lake vegetation transects.

The most omnipresent species was *Arctophila fulva*, which occurred in all 9 lakes. *Carex aquatilis* was present in all 3 "B" lake transects but was only present in 2 additional study lakes, C-2 and C-3. *Carex aquatilis* was not identified in any of the "A" lake transects; however, *C. aquatilis* is prevalent in shallow ponds in the Barrow area. *Dupontia fisheri* was prevalent in "A" lake transects, occurring in A-1

Table 7. Vegetation identified along transects in the 9 study lakes, Aug. 79.

Species	Northern Coastal Plain A-1	A-2	A-3	Mid-Coastal Plain B-1	B-2	B-3	Foothill C-1	C-2	C-3
Arctophila fulva	*	*	*	*	*	*	*	*	*
Carex aquatilis				*	*	*		*	*
Dupontia fisheri	*		*						
Eriophorum angustifolium							*[1]	*[1]	*
Caltha palustris					√				√
Potentilla palustris				√[2]					√
Petasites frigidus									√
Ranunculus gmelini					√				
Ranunculus hyperboreus	√[2]								
Eriophorum russeolum	√[2]								

* A species of major occurrence - densities of at least 1 stem/10 cm^2 observed

√ A species of minor occurrence - densities < 1 stem/10 cm^2 observed

[1] present at water's edge (shore) only
[2] not on transect, but in its vicinity

and A-2. *Eriophorum angustifolium* was present in the 3 "C" lake transects. Other species of minor occurrence are also listed in Table 7.

The densities of the most abundant species are illustrated in Figures 62, 63, and 64. Densities are shown as < 1 stem per 10 cm^2, 1-10 stems per 10 cm^2, or > 10 stems per 10 cm^2. The vegetation densities, water depths, and substrate types are compared with distances from shore.

The "A" lakes were dominated by *Arctophila fulva* and *Dupontia fisheri* (Figure 62). The emergent vegetation in Lake A-1 was abundant at the northeastern end in a marsh (Figure 28). Most of Lake A-1 beach is unvegetated gravel. Although the marsh is not particularly representative of the lake, it contained the only vascular vegetation associated with A-1. A vegetation transect was made through this marsh (wet meadow) on 1 August 1979. *Arctophila fulva* and *D. fisheri* occur mostly in separate stands (Figure 62). They overlap for a short distance at 30 and 100 m from shore in the A-1 transect. Changes in species and density occur simultaneously with changes in water depth. A large increase in water depth up to 67 cm at 40 m from shore resulted in no vegetation, while a similar water depth increase up to 70 cm at 70 m from shore was accompanied by a reduced vegetation density. *Arctophila fulva* was present in water more than 60 cm deep. *Dupontia fisheri* was restricted to water depths of less than 20 cm.

In Lake A-2, emergent vegetation was restricted to a few *A. fulva* stands at the southern end of the lake (Figure 62). The shoreline was abrupt, defined by a row of wave-heaped peat. A transect was made

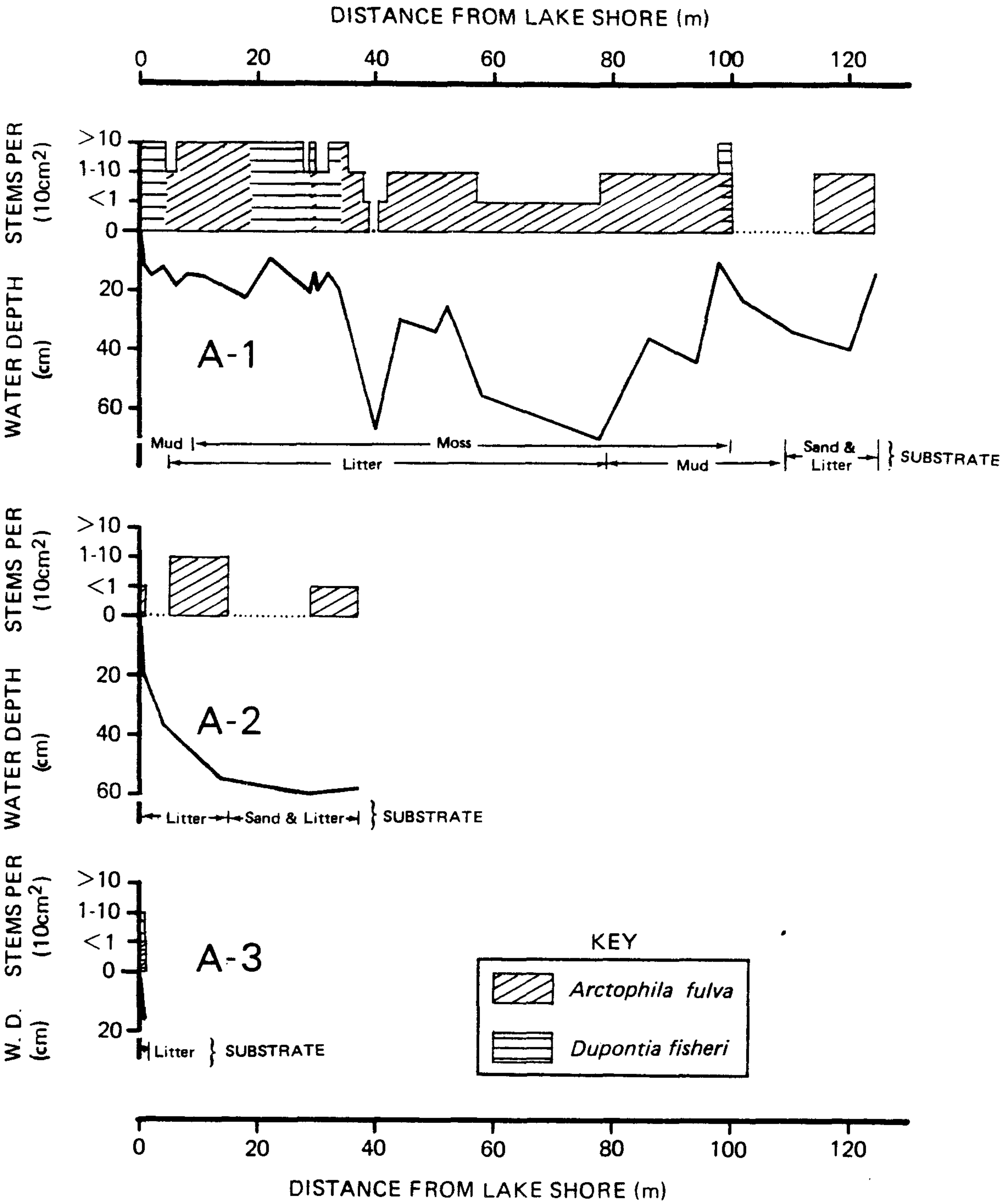


Fig. 62. Vegetation transects with water depth profiles in Northern Coastal Plain lakes A-1, A-2, and A-3, 1-2 August 1979.

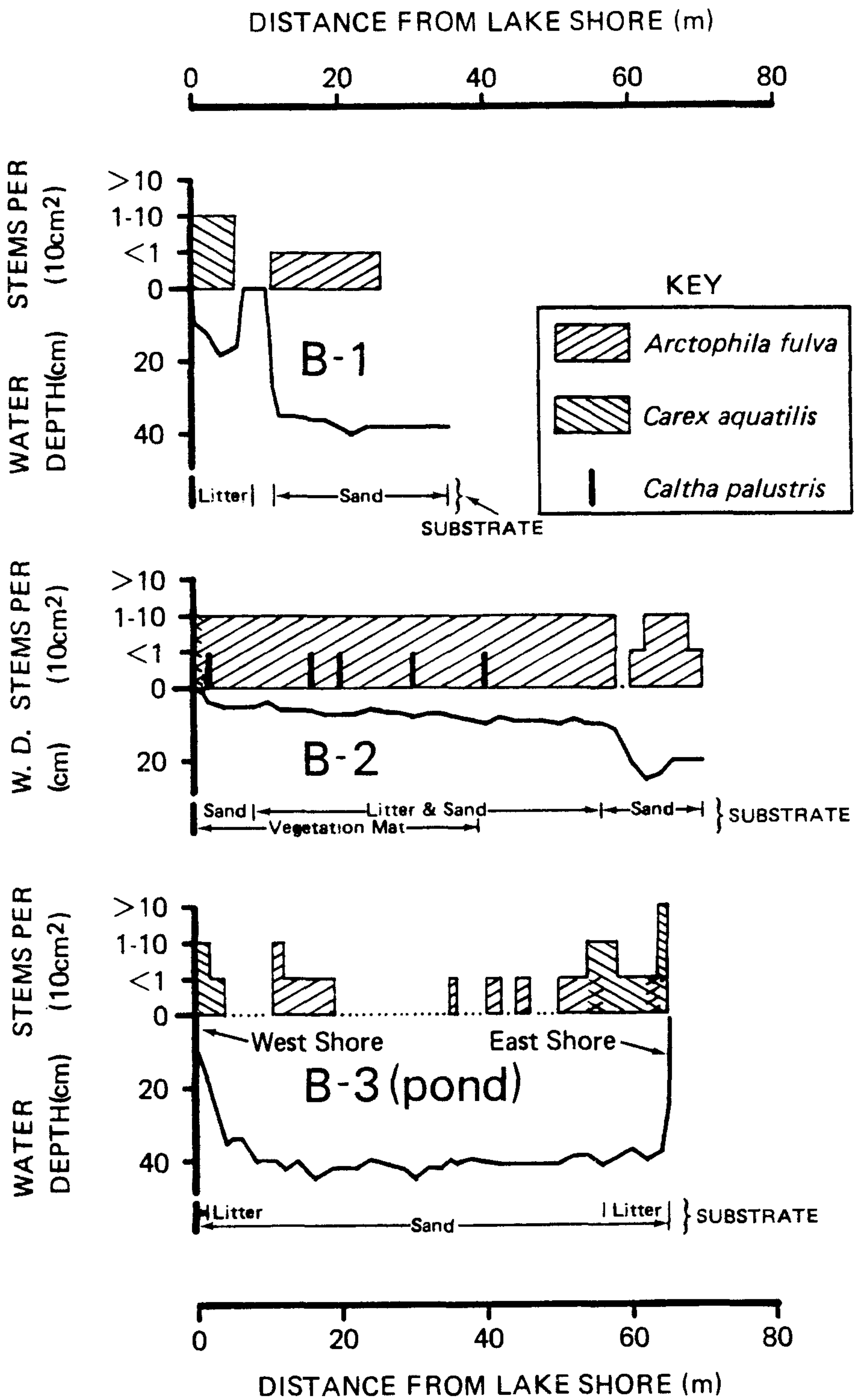


Fig. 63. Vegetation transects with water depth profiles in Mid-Coastal Plain lakes B-1, B-2, and B-3, 19 August 1979.

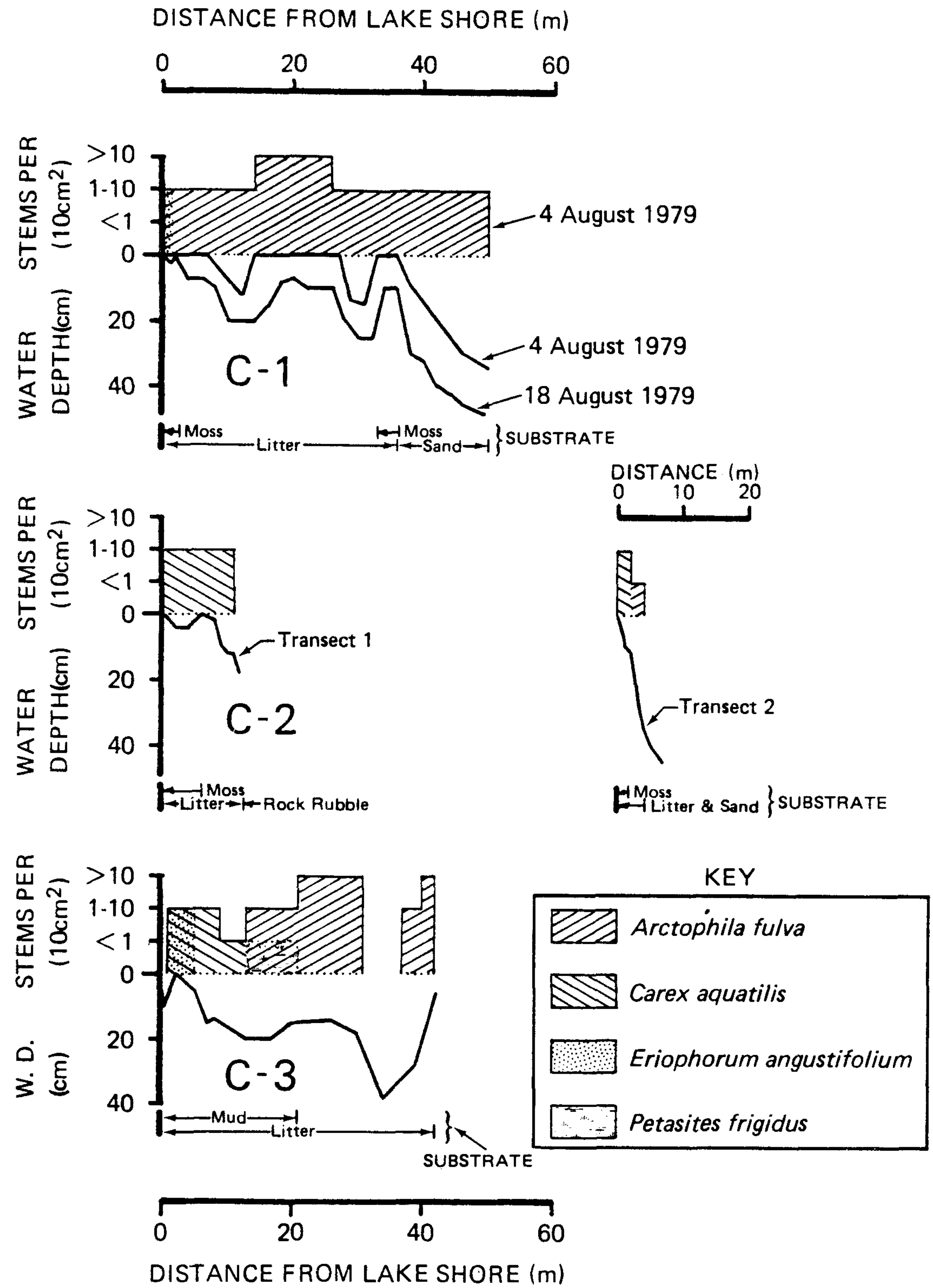


Fig. 64. Vegetation transects with water depth profiles in Foothill lakes C-1, C-2, and C-3, 4-18 August 1979.

through this stand of vegetation on 2 August 1979 (Figure 29). *Arctophila fulva* was the only species found and was present 37 m from shore in up to 58 cm of water. A wet meadow on shore adjacent to the transect was also composed of *A. fulva*, which extended for at least 100 m inland. This inland meadow was somewhat analogous to the marshy area studied as part of Lake A-1. Depth did not appear to be the limiting factor for *A. fulva* in A-2. The water depth was 40 to 50 cm for several meters beyond the last stand of vegetation occurring in 58 cm of water. The abrupt, wave-swept shores of the large lakes may have sufficient turbulence to limit vascular vegetation encroachment.

Lake A-3 emergent vegetation was restricted to about 25 *A. fulva* plants on the southern shore (Figure 62). A very short transect was made through these plants on 2 August 1979 (Figure 30). Some *D. fisheri* were also growing in a narrow band along the shore. The *D. fisheri* was transitional shore vegetation and extended less than 0.5 m from shore but had a higher density (10 stems/10 cm^2) than the *A. fulva* at < 1 stem/10 cm^2. Again, depth did not limit the plant growth in this shallow but wave-swept lake.

The "B" lakes have extensive shallow sandy shelves. At 50 cm depth the shelves are potentially available for aquatic vegetation colonization, although most of this area remains uncolonized. The major species identified in "B" lakes were *A. fulva* and *Carex aquatilis* (Figure 63). Little overlap occurred between these 2 species. All "B" lake transects were completed on 19 August 1979.

Lake B-1 had a few spotty patches of aquatic vegetation associated with peninsulas extending into the lake, some of which also supported terrestrial vegetation (Figure 63). A vegetation transect was made across one of these peninsulas at the southwestern end of the lake (Figure 31). It crossed a wet meadow with water from 10 to 18 cm deep in which *C. aquatilis, Potentilla palustris,* and moss species separated the wet meadow from the remainder of the lake basin. Large but sparse specimens of *A. fulva* occurred in water 40 cm deep for 17 m beyond the peninsula. The water was approximately 40 cm deep for a considerable distance beyond the end of the *A. fulva* stand.

Lake B-2 had a band of *A. fulva* surrounding the scalloped lake shore. *Carex aquatilis* occurred along the lake edge, which was difficult to define from the surrounding wet meadows. The transect was made across a wide stand of emergent vegetation between 2 peninsulas on the western shore (Figure 32). *Caltha palustris* occurred 5 times along the transect (Figure 63), and 1 specimen of *Ranunculus gmelini* was identified. *Arctophila fulva* stands were the most numerous, had seed heads, and were of small diameter in water 12 cm deep or less. Water 20 to 25 cm deep was populated with larger, less dense *A. fulva* that had no seed heads. The *A. fulva* stand stopped 70 m from shore, but water 20 to 25 cm deep continued beyond the vegetation terminus.

Pond B-3 was of a fairly uniform 40 cm depth and contained emergent vegetation throughout. The bathymetry of this pond was estimated from depths acquired for the vegetation transect. The transect spanned the pond from the western to the eastern shore. Wet meadows, populated primarily by *C. aquatilis*, surrounded the pond, and the same species extended into the pond 5 to 10 m from shore. *Arctophila fulva* was mixed with *C. aquatilis* near shore but occurred in pure stands in the pond center. *Arctophila fulva* was not dense and was absent in some areas. This and other adjacent ponds appear to have once been part of the deep lake basin to the east. The pond is presently separated from the lake by a 40 m wide bar of wet meadow containing some dryer hummocks populated with willows.

In the Foothill "C" lakes the dominant species was again *A. fulva*. Lake C-1 had the largest stand of emergent vegetation at the southwestern end of the lake (Figure 34). A transect was made through the widest part of this stand on 4 August 1979 (Figure 64). Water depths were re-measured at 2 m intervals on 18 August 1979. The water level had increased by about 10 cm between the two dates. *Eriophorum angustifolium* was abundant at the water's edge, but *A. fulva* was the only species present in the offshore stand. Much of the area in which *A. fulva* grew was devoid of water on 4 August; however, 8 to 10 cm of water occurred in these areas on 18 August. The plants in shallow water (0-10 cm) were small and numerous, while deeper water (10-40 cm) contained larger but less dense *A. fulva* specimens.

In Lake C-2, emergent vegetation was restricted to a few small stands on the northeastern side (Figure 35). Two transects were made across these small stands on 18 August 1979 (Figure 64). The first transect went through a stand of *C. aquatilis* that extended from the wet sedge meadow adjacent to the lake. Plants stopped at 12 cm water depth, 11 m from shore, but a litter and peat mat continued to a water depth of 35 cm, 15 m from shore. The adjacent wet sedge meadow was composed of *C. aquatilis, E. angustifolium,* and a few willows in water from 6 to 12 cm deep. The second C-2 transect went through a mixed stand of *A. fulva* and *C. aquatilis.* The *C. aquatilis* was, again, a continuum from the wet meadow to 12 cm water depth in the lake. *Arctophila fulva* occurred from 12 cm to a 35 cm water depth at 4 m from shore.

Lake C-3 contained several large stands of emergent vegetation. A transect was made across a stand on the southeastern end of C-3 on 4 August 1979 (Figure 36). The first 5 m of the transect was essentially a wet sedge meadow, with mixed stands of *E. angustifolium* and *C. aquatilis* and small amounts of *Caltha palustris* and *Potentilla palustris* (Figure 64). *Arctophila fulva* was the primary species, occurring from 13 to 42 m from shore. *Arctophila fulva* was not present in an area of deeper water (38 cm), 31 to 37 m from shore. Five *Petasites frigidas* plants occurred within the *A. fulva* stand in water 15 to 20 cm deep.

Arctophila fulva was the only species that occurred in every study lake and was also the dominant species in most lakes. Table 8 is a summary of the maximum density and limits of *A. fulva* occurrence in the lakes. *Arctophila fulva* was found immediately adjacent to shore in 5 lakes. Limits of water depth ranged from 0 to 70 cm. The maximum density was found in the 9 study lakes at a mean depth of 19.5 cm in a range of 0 to 55 cm of water. The mean maximum density was 8 stems per 10 cm^2 and the mean maximum limit of occurrence was in 38.8 cm of water.

Table 8. A comparison of *Arctophila fulva* occurrence in study lakes, Aug. 79.

	MAXIMUM DENSITY			LIMITS OF OCCURRENCE			
	# stems per 10 cm^2	Water depth (cm)	Distance from shore (m)	Water depth (cm)		Distance from shore (m)	
Lake No.				min.	max.	min.	max.
			NORTHERN COASTAL PLAIN LAKES				
A-1	25	15	9-19	4	70	0	124
A-2	7	40-55	5-15	5	58	0	38
A-3	1	7	0-1	7	15	0	1
			MID-COASTAL PLAIN LAKES				
B-1	2	36	18	25	39	10	24
B-2	5	1	1	0	25	0	62
B-3	1	40	10	10	43	0	36
			FOOTHILL LAKES				
C-1	16	0	14-27	0	34	1	50
C-2	<1	11-35	2-5	11	35	2	5
C-3	14	6	38-43	15	30	13	43

Spetzman (1959) produced an annotated list of plants growing in the Arctic. Aquatic vegetation information provided with this list includes ranges of water depth in which plants were found and distribution across the Arctic. Spetzman provided the following general comments on aquatic vegetation:

> "Very few kinds of higher aquatic plants grow on the Arctic Slope, and their distribution is erratic. Plant communities in each lake are usually arranged in concentric bands, corresponding to depth of water. Most vascular vegetation is limited to water less than 4 feet [1.2 m] deep, and the depth preferred by any given species decreases from the foothills northward into the more severe climatic conditions of the coastal plain. Each species forms an extensive colony, mostly by vegetative means, once it becomes established, thus excluding most other species...
>
> The principal aquatic plants are submerged rooted aquatics, which grow in as much as 4 feet [1.2 m] of water, emergent rooted aquatics, in 1 to 3 feet [0.3 to 0.9 m] of water, and marginal emergent aquatics, in less than 1 foot [0.3 m] of water."

Hobbie (1972) reported that distributions of *Carex* were limited to 15 cm water depth, and *Arctophila* occurred in water from 15 to 25 cm deep in a Barrow pond. Bergman et al. (1977) reported that distributions of *Carex aquatilis* were limited to 15 cm of water, *Arctophila fulva* occurred in between 20 and 45 cm, and 15 cm was the most frequent water depth interface between the 2 species. Bergman found no vascular plants in water depths exceeding 80 cm in the Teshekpuk Lake area, and that 3 species of *Eriophorum* often formed mixed stands with *Carex aquatilis*, usually in water depths of less than 10 cm near Storkerson Point.

Britton (1966) in his classic work on flora and vegetation of the arctic summarized the qualitative relation of vegetation to water depth in a thaw pond:

> "The deepest water of such a pond is occupied by *Arctophila fulva*, often with a mixture of *Hippuris vulgaris* and *Ranunculus pallasi*:...Peripheral to the *Arctophila* community, in increasingly shallow water, there may be successive communities of *Carex aquatilis*, *Eriophorum scheuchzeri*,... or *E. angustifolium*, and on saturated soils *Dupontia fisheri*... or *Alopecurus alpinus*."

Mosses and liverworts are common in the shallow water of pond/lake margins. Several species of sedges, in particular *Carex aquatilis* and *Eriophorum angustifolium*, dominate the wet sedge meadow environment (Spetzman 1959). Spetzman estimated that wet sedge meadow covered about half of the coastal plain. *Arctophila fulva* is a primary emergent species on the shorelines and shallow margins of lakes and ponds. Major groups and species of important vascular and pelagic flora are listed in Ecological Profile (1978), Netsch et al. (1977), and Derksen et al. (1977).

In this study, vascular aquatic vegetation occurrence was related to water depth. Vegetation stands were most often a single dominant species. Plant density changed with moderate variations in water depth, and species composition changed or terminated with rapid or large changes in water depths. The climatic gradient across the Alaskan arctic also produces changes in vegetation (Spetzman 1959, Britton 1966, Andreyev 1979), but the vegetation transects from the 9 study lakes were not enough samples to provide definitive distribution information.

Benthic Invertebrates

Benthic macroinvertebrates were sampled by an Ekman Dredge in each of the 9 study lakes. Samples were acquired from at least 0.5 m water depth and the deepest water that could be found during sampling. The organisms found are listed in taxonomic hierarchy in Table 9. The numbers of organisms found and counted from all lakes samples are summed and recorded for each taxonomic division. At the phylum level, arthropods were most prevalent, with 12,157 organisms counted, followed by relatively few annelids, mollusks, and nematodes. Pelecypods were more common than gastropods in the mollusk phylum. Oligochaetes were the most common annelid. Chironomids, with 9,255 organisms counted, were by far the most common organism found in the study lakes, and were also the most numerous insect. The cladocerans numbering 2,306 were the most numerous crustacean. The chironomids and cladocerans made up 95% of the organisms within the phylum Arthropoda and 83% of all the organisms counted.

Table 10 lists the number of organisms found in each of the 9 study lakes. Taxonomic groups below phylum are abbreviated with the first 4 letters of the names listed in Table 9. Table 10 identifies the lake, water depth at each station sampled, substrate volume sampled, and a qualitative description of the substrate. The sample volume indicates both depth of the Ekman Dredge penetration of the bottom and amount of material sieved and sorted. This volume is not directly related to the number of organisms counted because organisms are not distributed uniformly with depth and are concentrated at the surface. The counts were normalized to a surface area of approximately 0.05 m^2. Since each depth was usually only sampled twice, the combined sample cannot be considered statistically representative, but the replicate samples were

Table 9. A taxonomic list for Table 10 with total numbers of benthic invertebrates found within each taxon for the 9 study lakes, Aug. 79.

Taxon	No. of Organisms found
Phylum Nematoda (Nemathelminthes)	68
Phylum Molluska	515
Class Gastropoda	35
Class Pelecypoda	480
Phylum Annelida	1172
Class Oligochaeta	1141
Order Haplotaxida	1141
Class Polychaeta	2
Class Hirudinea (cocoons)	29
Phylum Arthropoda	12157
Subphylum Chelicerata	4
Class Arachnida	4
Order Acari	4
Suborder Prostigmata	4
Subphylum Mandibulata	12153
Class Crustacea	2883
Subclass Branchiopoda	2324
Division Eubranchiopoda	18
Order Anostraca	3
Order Notostraca	15
Triops longicaudatus (LeConte)	2
Lepidurus arcticus (Pallas)	11
Division Oligobranchiopoda	2306
Order Cladocera	2306
ephippia	2193
Family Chydoridae	89
Subfamily Chydorinae	83
Alona affinis (Leydig)	82
Alona (rectangula?)	1
Subfamily Eurycercinae	6
Eurycercus lamellatus	6
Family Daphnidae	24
Daphnia sp.	1
D. longiremis (Sars)	14
D. magna (Straus)	1
D. pulex (Leydig)	8
Subclass Ostracoda	354
Order Podocopa	354
Subclass Copepoda	205
Order Eucopepoda	205
Suborder Calanoida	113
Suborder Cyclopoida	92
Class Insecta	9270
Subclass Apterygota	2
Order Collembola	2
Family Isotomidae	2
Subclass Pterygota	9268
Division Endopterygota	9268
Order Trichoptera	6
Family Limnephilidae	6
Clostoeca sp.	6
Order Diptera	9262
Family Tipulidae	4
Family Empididae	3
Family Chironomidae	9255
Subfamily Chironominae	8337
Tribe Tanytarsini	7547
Tribe Chironomini	790
Subfamily Tanypodinae	191
Tribe Macropelopiini	191
Subfamily Diamesinae	5
Tribe Protanypini	5
Subfamily Orthocladiinae	722
Tribe Corynoneurini	1
Tribe Orthocladiini and/or Metriocnemini	695

Table 10. Benthic invertebrates (no. per .05 m^2 area) sampled Aug. 79.

Taxonomic Groups Found and Listed to Lowest Taxa Identified (see key Table 9)

numbers of organisms found (normalized to Ekman Dredge Sampling of ∿ .05 m^2)

Lake	Depth (m)	Samp. vol. (ℓ)	Substrate (see key)	Nematoda	Mollusca Gast	Mollusca Pele	Annelida Olig Hapl	Annelida Poly	Annelida Hiru	Arthropoda Chel Arac Acar Pros	Arthropoda Mand Crus Bran Eubr Anos	Noto *T. lo* *L. ar*	Olig Clad (ephi)	Chyd Chyd *A. af* *A. re*	Eury *E. la*	Daph *D. sp.* *D. lo* *D. mu* *D. pu*	Ostr Podo	Cope Euco Cala	Cycl	Inse Apte Coll Isot	Pter Endo Tric Limn *Clos*	Dipt Tipu	Empi	Chir Chir Tany	Chir	Tany Macr	Diam Prot	Orth Cory	Orth
A-1	0.5	1	R;SS	-	-	-	26	-	-	-	-	*	22	-	2	-	-	14	-	-	-	-	-	-	-	-	-	-	8
A-1	1.0	1	R;SS	-	-	-	54	-	-	-	-	-	14	-	-	-	-	20	-	-	-	-	-	18	-	-	-	-	66
A-1	2.0	1	R;SS	-	-	-	2	-	-	-	-	2	94	-	4	8	6	10	14	-	-	-	-	4	-	-	-	-	22
A-1	3.0	2	SS	-	-	-	2	-	-	-	*	2	-	-	-	-	-	6	38	-	-	-	-	-	2	-	-	-	4
A-2	0.5	2.0	SS;PT	4	-	-	-	-	-	-	-	-	6	-	-	-	-	-	-	-	-	-	-	3	3	-	-	-	11
A-2	2.0	1.8	SS;D;PT	3	-	-	81	-	14	-	-	11	>2000	-	-	14	13	1	14	-	-	-	-	3612	64	-	2	-	82
A-3	0.5	0.9	PT;SS	-	-	-	11	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	37
A-3	1.0	2.4	SS;PT	8	-	-	47	-	13	-	3	-	44	-	-	-	10	60	-	-	-	-	-	29	65	-	-	-	289
B-1	0.5	1.5	SA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8	4	-	-	-	-
B-1	10.0	4.0	SS;D;PT	-	-	37	162	-	2	-	-	-	-	-	-	-	7	-	2	-	-	-	-	25	35	7	-	-	-
B-2	0.5	1.2	SA	6	-	-	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17	16	1	-	-	5
B-2	1.5	1.3	SS;AS	-	-	18	5	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	46	20	-	-	-	7
B-2	2.0	2.4	SS;AS	-	26	150	25	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	435	30	-	-	-	-
B-3	0.33	1.7	SA	35	-	-	17	-	-	1	-	-	1	1	-	-	-	-	1	2	-	4	2	8	1	23	-	1	45
C-1	0.5	0.8	R;SS	-	6	-	56	-	-	1	-	-	-	-	-	-	2	-	-	-	2	-	1	139	54	7	-	-	16
C-1	4.0	0.8	SS;D	8	2	95	119	-	-	1	-	-	-	-	-	-	1	2	2	-	-	-	-	-	9	-	3	-	13
C-2	0.5	0.7	SA;PT;R;D	2	1	-	207	-	-	-	-	-	-	80	-	-	40	-	21	-	1	-	-	12	57	41	-	-	13
C-2	2.0	0.8	AS;SS;D	-	-	180	52	-	-	-	-	-	6	2	-	-	12	-	-	-	2	-	-	90	282	30	-	-	-
C-3	0.5	1.1	AS;SS;D	-	-	-	206	2	-	-	-	-	4	-	-	-	84	-	-	-	-	-	-	2712	88	54	-	-	100
C-3	1.0	2.1	AS;SS;D	2	-	-	56	-	-	-	-	-	-	-	-	-	179	-	-	-	1	-	-	389	59	28	-	-	4

D = Detritus
PT = Peat
SA = Sand
R = Rock & or pebbles
SS = Soft or fine sediment
AS = Aglutinated sediment (small balls)

* Parts (not whole animal)

consistent in type and numbers of organisms found. The qualitative identification of substrate type was also useful for lake depth comparisons of benthic chlorophyll *a* and primary production data.

Every lake was sampled at the 0.5 m depth. In most lakes, the numbers of zoobenthos were fewer at 0.5 m stations than at the deeper stations. This might be expected from wave mixing of these shallow substrates and the presence of ice throughout the winter. The substrates at 0.5 m were frequently coarser materials (i.e. sand, rock and/or gravel, and detritus). Samples from lakes C-1 and C-3 at 0.5 m were exceptions. In these lakes the chironomids were more numerous at 0.5 m than at the deep stations. The substrate types were similar at deep and shallow stations, and wave action was probably not significantly different throughout C-3. This would account for similar organism numbers, but does not justify greater numbers at the 0.5 m stations. Primary production was much higher at the 0.5 m depth than at 4.0 m or 1.0 m depths for C-1 and C-3, respectively. Another similar exception was that four times the numbers of organisms in the order Haplotaxida were found at 0.5 m depth in C-2 and C-3 than in the deep stations.

The 2.0 m depth samples contained the most number of species and most abundant zoobenthos. Although the numbers of zoobenthos sampled in Pond B-3 were not large, the number of species was. Most of the cladoceran ephippia were found in "A" lakes. Ostracods and copepods were much more numerous in "A" and "C" lakes than in "B" lakes. This is to be expected in lakes containing fish, as was the case in A-2, B-1, and C-1. O'Brien et al. (1978) and Kettle and O'Brien (1978) describe the selective predation of certain zooplankton by planktivorous fish. This will be discussed further with the fish/zooplankton results. Pelecypods occurred cnly in water greater than 1.5 m deep in "B" and "C" lakes.

Skreslet and Foged (1970) reported data with some variations in zoobenthos numbers in samples from different lake depths. They found different zoobenthos quantities within small increments of sediment depth below the water/substrate interface.

Inventories of benthic invertebrates in arctic lakes have been conducted by several investigators. Holmquist (1975) completed the most extensive inventory of lakes in northern Alaska and northwestern Canada. Fenchel (1975) studied the benthic microfauna of a pond near Barrow. Skreslet (1970) studied a Canadian arctic lake (Nordlaguna) on Jan Mayen Island and compared "zoobenthos" with water depths from which they were collected. Mozley (1979) did a survey of benthic macroinvertebrates, sampling a number of depths within each of 13 Alaskan arctic lakes. Nyquist (1973) acquired benthic samples from 0.3 and 1.2 m depth in an arctic lake near Prudhoe Bay. Few data were available in these surveys from which the organisms could be compared on the basis of different water depths from the same lake basin.

Mozley (1979) has acquired the only Alaskan arctic slope benthic macroinvertebrate samples collected at numerous depths within each lake basin sampled. Mozley sampled 2 shallow (1 to 2 m) coastal plain lakes that had moderately high zoobenthos densities in comparison with deeper (up to 22 m) foothill lakes that he sampled. They were dominated by chironomids, as were the study lakes. Zoobenthos density in Mozley's samples from the deeper foothill lakes varied greatly at different water depths, but he collected no (0.5 m) samples from shallow depths. Most of his samples were acquired at from 3 to 10 m depths. Mozley postulated that high zoobenthos densities in "coastal plain lakes may be partly attributable to reduced turnover rate". In lakes that freeze to the bottom, maturation is slowed from 1 year life cycles to from 2 to 7 years. More zoobenthos can coexist on the same food supply when the turnover rate is reduced.

In summary, the limited zoobenthos sampled did occur with greatest overall density and with more species at 2 m water depth. Zoobenthos were least dense at the 0.5 m depth in these samples. Chironomids were by far the most abundant; they occurred at all lake depths.

Zooplankton and Fish

During August 1978 at least 1 zooplankton net tow was made in each study lake. Lakes A-2, B-1, B-2, and C-1 were also sampled for fish with gill nets and fish traps during the summers of 1977, 1978, and 1979. Lake A-1 had already been determined to be devoid of fish, and the remaining lakes are believed to be too shallow to support overwinter fish populations. The results of fish and zooplankton investigations are presented in Table 3.

Fish were found in lakes A-2, B-1, B-2, and C-1; however, the only fish sighted in B-2 was a 4 mm long, dead ninespine stickleback. A 24 hour floating gill net and fish trap set failed to capture any fish in

B-2. The least cisco caught in A-2 may not overwinter, but may instead only use A-2 for summer residency, escaping through the outlet before freeze-up. Lake A-2 was sampled with 1 sinking and 1 floating experimental gill net and 4 baited minnow traps that were set for 27 hours. The floating net failed to catch any fish. The 4 traps caught 2 ninespine sticklebacks. The sinking gill net caught 4 female and 3 male least cisco which ranged in size from 205 to 330 mm fork length and weighed from 113 to 539 g. Fish may but probably do not overwinter in A-2. Deep lakes B-1 and C-1 are the only study lakes certain to have a year-round resident fishery. Lake B-1 contains least cisco and ninespine sticklebacks. One floating experimental gill net set for 24 hours caught 22 least cisco on 22 August 1979. They ranged in weight from 100 to 690 g, with a mean weight of 325 g. The fork lengths ranged from 242 to 377 mm, with a mean length of 304 mm. Lake C-1 was sampled by the Alaska Department of Fish and Game from 7 to 9 August 1977. The catch effort was 1 floating and 1 sinking gill net, each set for 12 hours, and 8 man hours of angling. Lake trout, arctic grayling, and broad whitefish were caught.

Alaska Department of Fish and Game (1977) and Netsch (1977) have completed fishery surveys on Arctic lakes for the National Petroleum Reserve in Alaska, Task Force (U.S. Dept. of the Interior 1978). The description of fish habitat resource values is still limited to minimal summer sampling and site data. This data indicate that Arctic lakes are frequented by the following 11 species of fish:

*1.	arctic grayling	*Thymallus arcticus* (Pallas)
2.	arctic char	*Salvelinus alpinus* (Linnaeus)
3.	arctic cisco	*Coregonus autumnalis* (Pallas)
*4.	least cisco	*Coregonus sardinella* Valenciennes
*5.	lake trout	*Salvelinus namaycush* (Walbaum)
*6.	broad whitefish	*Coregonus nasus* (Pallas)
7.	round whitefish	*Prosopium cylindraceum* (Pallas)
8.	humpback whitefish	*Coregonus pidschian* (Gmelin)
9.	slimy sculpin	*Cottus cognatus* Richardson
10.	alaska blackfish	*Dallia pectoralis* Bean
*11.	ninespine stickleback	*Pungitius pungitius* (Linnaeus)

*Found in at least one study lake.

Oligotrophic waters and thick winter ice limit the fish numbers, species, growth rate, and lake habitat availability in arctic lakes. Power (1978) completed a fish population structure investigation in Canadian arctic lakes. His study populations contained many small, few intermediate, and many large fish. Power proposed that population structure was the result of relatively rapid growth until maturity, with slow growth through the remaining life span, which may exceed 50 years. Predation and mortality are high in young fish.

Extensive sampling for arctic lake zooplankton has been done by Reed (1962), Kangas (1972), Nyquist (1973), and O'Brien (1974). Some relationships between pond zooplankton species occurrence versus chemical and physical variables were evaluated by Kangas (1972). Gradients of maximum lake depth and arctic climatic gradient have not been considered in these past studies. O'Brien (1974), Kettle and O'Brien (1978), and O'Brien and Kettle (1978) discussed the presence of fish relating to the occurrence of zooplankton species. Fish are limited to basins with water depths that exceed maximum winter ice thickness or basins with outlets that provide corridors for summer migration. O'Brien (1974) found that *Daphnia middendorfiana* and *D. pulex* occurred more frequently in shallow lakes where fish were not present. *Daphnia longiremis* occurred in the opposite fashion, being absent from lakes without fish, but present in those containing fish. *Daphnia middendorfiana* is probably a more efficient competitor with *D. longiremis* and is prevalent in lakes not containing fish. *Daphnia middendorfiana* is selectively preyed upon by planktivorous fish and is eliminated as a *D. longiremis* competitor from lakes containing fish (O'Brien 1974, Kettle and O'Brien 1978, O'Brien and Kettle 1978). This phenomenon has been referred to as the size-efficiency hypothesis (Brooks and Dodsen 1965), where large zooplankton species can usually outcompete smaller species but are more susceptible to predation.

In agreement with O'Brien's (1974) postulation, *D. middendorfiana* occurred only in lakes without fish, and *D. longiremis* occurred only in lake A-2 that contained cisco and ninespine sticklebacks (Table 3). Zooplankton counts were too varied to justify any attempt to correlate zooplankton occurrence with latitudinal gradient or maximum lake depth of the study lakes.

Because of winter ice, lakes less than 2 m deep generally do not have resident fish populations. During the summer, ice-free season, fish distribution may be limited by the existence of outlets suitable for migration, water quality, and/or substrate suitability for spawning. In the "A" lakes where lakes tend to be shallower and ice thicker than in "B" and "C" lakes areas, fewer suitable fish overwintering areas are present. The only zooplankton correlation, that could be inferred from the information obtained during this study and cited references, is the presence or absence of those species that are associated with the presence or absence of fish. Since fish occur primarily in lakes more than 2 m deep, some variation in zooplankton species might be expected in lakes less than 2 m versus those greater than 2 m deep.

SUMMARY

Nine lakes within a transect across the Alaskan arctic were sampled for biological, chemical, and physical characteristics to investigate constituents that vary with changes in water depth and latitude along the transect.

The climatic gradient, particularly wind and marine influence at the northern end of the transect, affected specific conductance, suspended sediment loads, and light attenuation differently along the transect. The morphology of lake basins changed across the transect, with deeper basins occurring in the middle and southern regions than in the northern. Variations in algal biomass (chlorophyll a), summer and winter temperatures, winter dissolved oxygen, and ice cover measurements were related to differences in climate across the transect.

According to the literature, primary production and vascular emergent vegetation should vary with latitude, but the data collected were of insufficient scope to verify these differences.

All constituents sampled, except summer pH, alkalinity, and nutrients, showed some correlation with water depth. Many of the water depth relationships are produced by physical factors such as wind-generated waves and ice accretion, which affect these shallow (0 to 3 m) aquatic environments most significantly. Wind-generated wave mixing in shallow water causes sorting of benthic substrate materials, changes in water column suspended sediments and light attenuation, possible nutrient replenishment from resuspended sediments, and quantitative shifts in benthic versus water column chlorophyll *a* and primary production measurements. Shallow basins and/or shoals within deep basins are the most severely affected by wave action. Primary production was limited by light at or near the water depth at which the 1% light level occurred. When shallow lake and pond substrates receive plentiful light, they may have much greater benthic than water column primary production. The reverse is the case in deep or turbid lakes where little to no light reaches the bottom. Total algal primary production is related to total light utilization whether by benthic algae or phytoplankton. This suggests that the potential for total benthic plus water column primary production should be the same in deep or shallow water if all other variables remain the same. Emergent vascular vegetation species are limited to specific ranges in water depth.

Ice accretion causes a percentage reduction in free water volume that is inversely proportional to lake depth, which in shallow lakes causes rapid increases in specific conductance, depletion of dissolved oxygen, limited fish and zooplankton habitats, and near freezing temperatures in the remaining water. The number of columnar gas bubbles incorporated in ice cover decrease over lake areas > 2 m deep to few to none in lake areas > 4 m deep. Ice limits the lake depth range of benthic invertebrate species intolerant of frozen habitat. Overwintering fish require lake depths greater than maximum ice thickness. Most of the summer's heat is used to melt thick ice cover leaving little to heat the water column of deep lakes. Ice on shallow basins melts early allowing sediment and water to attain very warm summer temperatures.

This investigation concentrated on some baseline sampling of many constituents rather than extensive sampling of a few. Many of the water depth/constituent relationships require further study to define, refine, or quantify the associations highlighted here. These results show that water depth is a major factor in predicting aquatic constituents associated with Alaskan arctic lakes, and indicate that water depth is the best single parameter that can be used to classify and define the resource potential of all arctic lake habitat.

CHAPTER IV

DISCUSSION--APPLICATIONS FOR REMOTELY SENSED AQUATIC INVENTORY DATA

CONSTITUENTS/RESOURCES ASSOCIATED WITH RANGES OF WATER DEPTH

In order to evaluate the validity of using SLAR determined water depth contours to inventory or assess aquatic resources, ranges of depth that might be assessed with SLAR were selected and compared with aquatic constituents and resources associated with arctic lakes and wetlands. Water depth categories that could reasonably be distinguished using the SLAR methods discussed in Chapter II are: 0-0.5 m, 0.5-1.0 m, 1.0-1.5 m, 1.5-2.0 m, 2.0-4.0 m, and > 4.0 m. Water within these depth ranges is affected differently by winter ice formation and by summer winds and light penetration. The first 3 depth categories (0-1.5 m) have winter ice growth to the lake bottom, summer vascular aquatic vegetation, and are affected by the most severe summer and winter environmental extremes. In the 1.5 to 2.0 m category, depending upon latitude and winter severity, ice forms to or very close to the lake bottom. Lake basins with 2.0 to 4 m depth are in a marginal environment, where mid-winter conditions may be extreme, yet some water remains unfrozen throughout the winter. These lake basins always have some free water within the basin that is available for use by industry, the public, and/or the flora and fauna of the natural habitat, but water volumes required to sustain fauna may limit water withdrawal. However, basins with water depths > 4 m may have sufficient water volume to sustain fauna and water withdrawal. Deeper basins have less severe winter conditions and, therefore, a greater chance to sustain a year-round fish population. Most of the water in Arctic Coastal Plain lakes is turned to ice by mid-winter; thus, resources associated with water depth are controlled or limited. Ice, however, is not the only control. Turbidity and light penetration, bottom substrate, available nutrients, watershed, basin morphology, specific conductance and other factors, many of which have already been discussed, can affect resources associated with any water body. Table 11 is used to relate the selected water depth categories with aquatic constituents obtained during this study and with Arctic resources associated with lakes and wetlands.

The lake constituents summarized in Table 11 are temperatures, primary production, light extinction, and suspended sediment load in the summer and salt concentrations or specific conductance, dissolved oxygen, and water temperature extremes under ice cover.

The lake resources included in Table 11 are free water availability, fish overwintering, emergent vascular vegetation presence, waterfowl usage, and transportation usage of lake water and ice by aircraft and other off-road vehicles. Results from this study, in addition to the literature, were used to describe fish and emergent vascular vegetation associations with water depth, while other resource associations (i.e. water availability, fish overwintering, and aircraft or off-road vehicle usage) have been inferred from ice thickness data. Waterfowl usage was determined from Bergman et al. (1977). This discussion follows the organization in Table 11 with estimates or

Table 11. Arctic lake/pond characteristics associated with six categories of water depth.

RANGES OF WATER DEPTH		LAKE CONSTITUENTS									LAKE RESOURCES						
		Potential for Primary Production		Summer Light Extinction & Suspended Sediments Loads	Salinity Concentration at Lake Bottom	Potential for Winter Depletion of Dissolved Oxygen	Potential for Extreme Water Temperatures		Ice Cover Comments	Free Water Available (Months)	Potential for Fishery Over-wintering	Potential for Emergent Vascular Vegetation	Waterfowl Usage (Months)	Aircraft Usage (Months)		Light Aircraft and Off-Road Vehicle Use of Ice Cover (Months)
Category	(m)	Water Column	Benthic		Mid-Winter		High in Summer	Low in Winter						Floats	Hercules Ice Strip 1.2 m of Ice	
1	0 to .5	M to H	L to H	H	H	Total (ice)	H	H (ice)	Freezes to the bottom by December and melts first in spring; used by early spring waterfowl	June thru Sept.	N	H	June to Sept.	N	Dec. to late Sept.	Nov. to late Apr.
2	.5 to 1.0	H	M to H	H	H	Total (ice)	M	H (ice)	Freezes to the bottom by February and melts soon after the 0-.5 m Ice	Late June thru Nov.	N	M to L	June to Sept.	Early July to Sept.	Jan. to May	Nov. to May
3	1.0 to 1.5	H	H	M	H	Total (ice)	M	H (ice)	Freezes to the bottom by April usually	July thru Jan.	N	Very L	July to Sept.	July to Sept.	Feb. into May	Nov. to May
4	1.5 to 2.0	H	H	M to L	H to M	H	M	M	May not freeze to the bottom entirely, melt may last well into July	July thru Mar.	Very L	N	July to Sept.	July to Sept.	Late Feb. into May	Nov. to May
5	2.0 to 4	M to H	M to H	L	M	M	M	M	Does not freeze to bottom; may last into late July	All year	L to M	N	July to Sept.	Late July to Sept.	Late Feb. into May	Nov. to May
6	>4	M to L	H to L	Very L	L	L	L	L	Never freezes to the bottom; very late melt and breakup which may last into late July or early August	All year	H	N	July to Sept.	Late July to Sept.	Late Feb. into May	Nov. to May

Key: H = High; M = Medium; L = Low; N = None generalizations made from data taken from both this study and/or the literature cited. Some of the data are limited in temporal, spacial, and sample number extents.

The primary production (PP) estimates for water column and benthic substrates are considered separately. The greatest water column PP usually occurs at from 0.5 to 6 m depth, depending on turbidity and light attenuation. The water column PP may be reduced in the upper layer from light inhibition. Water column PP begins decreasing at about the 1% incident light level and continues to decrease with depth.

Benthic PP may be inhibited in shallow substrates by light, coarse substrate material and/or wave scouring of benthic algae. Benthic production tends to increase with depth until limited by light attenuation.

The productivity of arctic terrestrial and aquatic ecosystems is low. Arctic lakes with relatively high rates of production have about the same order of magnitude production as the least productive of temperate lakes (Frey and Stahl 1958). Shallow lakes have a higher intensity of primary production per unit volume than deep lakes.

High summer light extinction coefficients caused by suspended sediments loads in Arctic lakes are primarily the result of winds producing waves that resuspend bottom sediments. The depth of a lake, wind persistence and velocity, lake fetch and substrate type are all important factors in determining the turbidity of the water column. In general, the extinction coefficient and suspended sediment loads diminished with increasing maximum lake depth. Deep lakes offer a settling basin for fine sediments and tend to have coarser material on the shelves that is not readily wave mixed into the water column. Large Northern Coastal Plain lakes in the 0 to 1 m depth categories are most susceptible to high suspended sediment loads and light extinction coefficients.

Salinity, dissolved oxygen, and temperature are constituents that stress organisms living in the shallow bodies of water. Pond and lake shallows in the shallowest 3 depth categories are frozen to the bottom during the winter. During ice formation, as the volume of water under the ice becomes limited, temperatures approach freezing and constituents within the water column become concentrated in the limited remaining water. Dissolved salts concentrate within this limited water. Specific conductance or salinity continues to increase near the lake bottom until all water has turned to ice in lakes up to 2.0 m deep. The severity of this salinity concentration is in part a result of initial salt concentrations, which may be particularly high in the shallow lakes along the Arctic Ocean Coast. Some salt concentration occurs in lakes deeper than 2.5 m but is inversely proportional to the percentage of lake water remaining unfrozen beneath the ice cover. The greatest salinity fluctuations, which may produce osmotic stress for winter aquatic fauna, occurs in lakes that freeze to or very near to the bottom.

Dissolved gases in the water column act in much the same way as the salts during ice formation. The dissolved gases are concentrated in the remaining water column until they reach saturation and come out as gas bubbles. The gas then becomes frozen into the ice cover in elongate bubbles. Respiration continues and microbial oxidation increases under the ice and snow cover that has: consumed some of the dissolved oxygen (DO) from the water column, barred replenishment from the atmosphere, and reduced DO production from photosynthesis by attenuating light. The DO available during mid-winter becomes proportional to the volume of water remaining and inversely proportional to the microbial oxidation of summer organic matter production. If free water is limited to 1 m or less, respiration can deplete the water column of all DO. Most of the Alaskan arctic lakes that are less than 3 m deep probably have a severely depleted DO of less than 3 ml/ℓ by April.

Temperatures are most extreme in shallow waters. Summer temperatures are highest in shallow ponds, which melt early and warm quickly. The deep lakes do not warm up as much in the summer, but they maintain warmer, moderate temperatures in the winter. Ice freezes to the bottom of lakes in the shallowest 3 depth categories. Lakes from 2 to 4 m deep do not usually freeze to the bottom, but water temperatures approach 0°C near the ice/water interface. Lakes > 4 m deep may maintain water temperatures between 0 and 4°C, with warmer temperatures near the water/substrate interface.

The ice cover comments in Table 11 are self-explanatory and provide the basis or rationale for much of the discussion to ensue on aquatic resources associated with water depth categories. The month by which all lakes should freeze within a specific category or depth range has been estimated for each category. This was the month by which the average ice cover on all study lakes had reached a thickness equal to the maximum depth for the category. For example, lakes in the second category with a maximum of 1 m depth were completely frozen by February. These estimates were made from winter 1978-79 study lake ice thickness data (Figure 44).

Free water availability refers to liquid water potentially available for wildlife, domestic, and industrial use. Dates that this resource is available range from all year to 4 months during summer (Table 11). The upper month is an estimate of the month during which break-up should occur at the greatest depth within the depth category. The lower month is an estimate of the month during which freezing begins at the shallowest depth within a depth category. For example, in the 0 to 0.5 m category, freeze over of surface water usually occurs in September and break-up is usually complete to depths of 0.5 m in June. Likewise in water depths from 0.5 to 1 m, freezing of water at 0.5 m depth occurs during November, and break-up of 1 m deep ice occurs in late June. Break-up of from 1 to 2 m deep ice varies over a few weeks but occurs for the most part within the month of July. Water at 1 m and 1.5 m depths freezes during January and March, respectively. Water at depths greater than 2 m usually remains ice-free throughout the entire year.

Ice and liquid water in the lakes and rivers are used by village residents and industry for utilities, potable water, civil construction, transportation, food gathering, recreation, oil well drilling, and waste disposal. These uses can and have conflicted with wildlife use. Any action or water use that reduces the quality of the aquatic environment also limits its value. Human and industrial uses can cause reduction of water quantity or quality. Water is a limited resource in the Arctic because the amount of precipitation is small (10 to 25 cm annually), and lake basins are typically shallow.

Ice strips are maintained on many lakes throughout the winter. Multiple-use conflicts can arise if, for example, aircraft refueling contaminates lake water. Where snow insulation is removed for ice landing strips, ice thickness increases, thus reducing the liquid water content of the lake basin. The detrimental biological effect of these sorts of activities has not been quantified but is recognized to be a potential problem under certain conditions.

Ice is ripped from the surfaces of ponds and lakes, and/or water is pumped from beneath the ice for winter ice road construction. Approximately 113 km (70 mi) of ice roads, requiring roughly 2.4 million liters of water per km (1 million gallons per mile), were constructed for oil exploration within the National Petroleum Reserve-Alaska (NPR-A) during the 1977-78 winter season (Ecological Profile 1973). This ice and water removal causes deeper freezing or less available free water, thus freezing aquatic habitat that would otherwise not have frozen. Sessile and quiescent fauna then are frozen and motile fauna become concentrated or susceptable to death from freezing.

Fish cannot overwinter in ponds or lakes that freeze solid, those with depths to 1.5 m. Lakes in the range of from 1.5 to 2.0 m deep may provide some unfrozen or barely frozen microclimatic habitats suitable to the Alaskan blackfish (*Dallia pectoralis*) and/or the ninespine stickleback (*Pungitius pungitius*). The survival of these fish has been a subject of conjecture for years (Holmquist 1973). Neither of these 2 species can survive freezing solid. The primary overwintering fish habitat exists in lakes more than 3.0 m deep. The deeper the lake, the greater the potential for fish.

Emergent vegetation may occur in shallow (0-1.5 m) margins of deep lakes in addition to basins that are shallow throughout. *Potamogeton, Ranunculus*, and *Sparaganium* occur in water depths up to 1.3 m, and *Arctophila fulva* and *Hippuris vulgaris* dominate waters of from 0.3 to 1.3 m (Spetzman 1959). *Carex aquatilis* is a common, dominant species in ponds and lake margins 0 to 0.5 m deep. In this study, *Arctophila fulva* was found to 0.7 m and *Carex aquatilis* to 0.4 m. The potential for occurrence of vascular aquatic vegetation varies indirectly with increasing water depth to 1.5 m, and is lacking beyond that depth. Aquatic vegetation is an important part of the aquatic ecosystem. It provides a major contribution to primary production, escape habitat and food for waterfowl, and a niche for invertebrates. Vegetation is also a factor in the evolution of basin morphology.

The waterfowl usage of ranges of water depth, estimated by month, is predicted on the presence of open water within the ranges of water depth in Table 11. The early arctic arrivals must be opportunistic. Waterfowl can land on and feed from the shallow areas that become ice-free early in the summer season (June). Bergman et al. (1977) and Derksen et al. (1977) describe a variety of wetland classes and identify water bird associations with these classes. In general, water birds disperse into deeper lakes as these lakes become ice-free in July but continue dominant usage of lakes and ponds with emergent vegetation and good invertebrate food sources. Waterfowl utilize deep lake habitat frequently when emergent vegetation is abundant along a shallow shore. Fish feeding birds (loons) frequent the deeper lakes containing fish. All waterfowl depart the arctic before all surface water freezes, usually in mid-September but sometimes as late as early October.

Invertebrates provide a medium for energy transfer out of the aquatic ecosystem through birds. Wet sedge meadows are flooded during at least the first half of the summer providing an environment for early production of diverse invertebrate populations, including fairy shrimp, springtails, snails, water fleas, and midge larvae (U.S. Dept. of the Int. 1977). Waterfowl and shore birds utilize these shallow wetlands (wet sedge meadows) for early summer feeding before ice melts from deeper lakes. Some shorebirds, especially plover, continue to use these wetlands as surface water is reduced in extent thus concentrating the invertebrate food source. The reproductive success of many bird species is intimately tied to productivity of tundra lakes and ponds (Bergman et al. 1977). He reported 27 bird species associated with lakes and lake edges, 20 species in conjunction with wet sedge meadows, and 19 species with flowing water. Bergman et al. (1977) found 30 species of birds required wetlands for nesting, foraging, and/or molting (escape habitat).

Traditional use of specific lakes by water birds cause high nutrient input. Variations in concentrations of chlorophyll and species of invertebrate fauna in arctic lakes must, in part, exist as a result of variations in vertebrate fauna associated with a particular volume and depth of water. Water birds transfer nutrients and energy from the aquatic environment to land, in addition to keeping the rate of nutrient turnover higher in lakes and ponds frequented. Tundra ponds too shallow to support fish populations still play an important role in the ecology of the Arctic Coastal Plain because of water bird utilization (Bergman et al. 1977, Bunnell et al. 1975). Vegetation and invertebrate production in lakes and ponds is vital to water birds.

Roads are sparse in the Alaskan arctic. With the exception of the trans-Alaska pipeline road and the Prudhoe Bay road complex, less than 30 miles of gravel road exist. All equipment and supplies, including those that support the NPR-A petroleum exploration program, must be moved by aircraft operating on water, ice, or gravel airstrips or by overland travel.

Ice 0.2 to 0.3 m thick is sufficient for most small aircraft and light surface vehicles. The lake ice may attain this thickness by November, providing flat, surface-traffic transportation corridors away from the tundra until spring melt begins (Table 11). The shoals surrounding even large lakes are the first to melt in the spring, leaving moats that preclude the use of lake ice for travel. This usually occurs in April or May in southern arctic areas and as late as early June in northern areas.

Float-equipped aircraft operate off ice-free lakes > 0.5 m during the summer months from July until freeze over in September. Lakes in the 0 to 0.5 m depth category are ice-free in June but most have too small surfaces and are too shallow for aircraft to land on them safely.

The major overland movement of equipment and supplies occurs during the winter months. Hercules aircraft (C-130) are used extensively in the arctic. They require a landing strip approximately 1,500 m long. The smooth, flat surfaces of frozen lakes make economical winter landing strips. If the strip is on lake ice over water, the ice must be at least 1.2 m thick. The ice may be less thick if the lake is frozen solid. Shallow basins 0 to .5 m deep may be used from December to April, during which time they are solidly frozen (Table 11). The 0.5 to 1 m deep basins do not freeze to the bottom until January. Lakes in this category can be used from January until the first stages of melt, which may start in May. Similarly, the third category of 1.0 to 1.5 m deep lakes freeze solid or attain 1.2 m ice thickness by late February, as do the deeper lakes. The dates provided may vary due to annual climatic variations and individual lake conditions. In order to use deep basins earlier in the season, workers can increase ice thicknesses by flooding the ice surface with lake water rather than wait for natural ice accretion.

Overland travel is generally restricted to the winter months when the tundra is covered with snow and is frozen sufficiently to support vehicles without being damaged. Tundra vegetation is not affected when frozen lake surfaces are used for landing aircraft and surface vehicle movement.

EXAMPLES OF WINTER SLAR IMAGE USE FOR ASSESSMENT OF LAKE RESOURCES

The SLAR imagery acquired during this study can be analyzed for the presence or absence of lake constituents and resources discussed above.

Study Lakes

SLAR images of lakes B-1 and C-1 had bright interiors with subtle gray-tones within these bright interiors, indicating depths > 4 m. These were, in fact, the deepest basins, and probably contained the only overwintering fish populations within the study lakes. These lakes obviously have the potential for supplying water from beneath an ice cover that lasts from October to July. They have little chance of becoming depleted in dissolved oxygen, high in salt content, or limited in space beneath the ice cover. Summer suspended sediment loads and light extinction should be and were low in comparison with shallower nearby lakes.

The SLAR images of A-1 continued to become darker shades of gray with each successive winter image. This indicated that water existed below the ice cover and was becoming more saline as the winter progressed because salts were concentrated in the limited volume of water. The salts and limited water volumes could also indicate the lack of fish noted during this study. The A-1 images had a dark area on the northeastern lake shore that was the marshy shoal, which was frozen to the bottom.

SLAR images of lakes A-2, B-2, C-2, and SLAR-1 had uniformly bright lake centers throughout the entire winter 1978-79. This indicated moderate depths (2-4 m) with water beneath the thickest winter ice; however, because of the moderate depth there exists the potential for extreme environmental conditions (i.e. depleted dissolved oxygen, low temperatures, increased salinity and limited water volumes). Since these conditions are prevalent there exists little chance for an overwintering fish population.

April, 1979 SLAR images of lake basins B-1 and B-2 had dark perimeters, delineating extensive shallow shelves adjacent to a deeper basin. During the study, these shelves were found to be sandy with low benthic algal biomass and have the potential to support emergent vascular vegatation. The slightly deeper areas outside the shelf break have mud bottoms with high benthic algal biomass.

May 1979 images of lakes A-3, B-3, C-3, SLAR-2 and SLAR-3 were dark throughout, indicating that the lakes were completely frozen to the bottom by May. Pond B-3 was shown to be frozen to the bottom in the first image acquired December 5, 1978, while successive images indicated that the other shallow lakes were frozen by the following image dates: A-3 and C-3 February 21, 1979, SLAR-2 March 20, 1979, and SLAR-3 May 15, 1979. Prior to these dates, winter water could have been used without fear of such shallow lakes containing fish. After these dates the ice was frozen to the lake bottom, providing a safe surface for large aircraft landings or tractor train moves. Lake A-3 was used for landing aircraft as was interpreted from the February 21, 1979 image in Figure 14. During the summer these lakes could be expected to melt earlier, to attract early waterfowl usage, to have higher suspended sediment loads and light extinction coefficients, lower benthic algal biomass, and higher potential for emergent vascular vegetation than the deeper basins.

April 1980 SLAR Images over NPR-A

Although ice on the Northern Coastal Plain continued to grow until mid-May 1979, near-maximum ice thickness across the entire Alaskan arctic study area was achieved in April. Water content within ice beginning to melt caused reduced SLAR image definition for lake depth information in 15 May 1979 imagery. April was determined to be the best month during which to acquire SLAR images for defining winter water availability in lakes with near-maximum ice thickness. Overlapping SLAR imagery was acquired over approximately 90% of the National Petroleum Reserve in Alaska (NPR-A) from 7 to 11 April 1980 (Appendix A, Figure A-1). The data are reported here to document all SLAR and ground verification data acquired during the course of this study, in addition to providing an example of the use of SLAR data for water use management on NPR-A. Ground verification data were collected from lakes distributed across NPR-A (Appendix A, Figure A-2) rather than just within the study transect and are reported in Appendix A, Table A-1. These 6 to 15 April 1979 data have been used, in part, in previously discussed dissolved oxygen, Figures 48 and 49, temperature, Figure 45, and Table 5. They were acquired especially, however, to determine ice thicknesses throughout NPR-A for the time during which the SLAR imagery was acquired. The SLAR imagery is on file at the Bureau of Land Management NPR-A Office in Fairbanks, Alaska. It has been used to help assess lakes in the vicinity of 7 oil exploration well sites that the U.S. Geologic Survey proposed for FY 1981 drilling. The data will continue to be useful in successive years for preliminary office assessment for the presence or absence and the geographic location of liquid freshwater within lakes with thick April ice cover. These same areas may also sustain fish populations and are checked for safe water withdrawal limits prior to use. The same SLAR lake images can be used to define shallow lake areas that might be frozen to the bottom soon enough in the winter freezing season for early placement of ice landing strips and winter trails.

COMPUTER GENERATION OF A LAKE DATA FILE FROM LANDSAT DIGITAL DATA

Introduction

The computer system described here identifies discrete lakes and acquires lake surface information from Landsat satellite digital data. The system was developed because of the potential for a substantial increase in the data base for Alaskan arctic lakes and the need for consolidating this information into a single organized source. Chapters II, III, and IV demonstrate the potential for remote-sensing systems adding to this data base; for example, SLAR images may be used to determine the areal extent of fresh water under maximum winter ice thickness and lack of fish in Alaskan arctic lakes which are frozen to the bottom.

The computer system uses Landsat digital data to identify surface features (i.e. lake center, area, perimeter, and crenulation) and create a file containing this information. The system has worldwide application for large flat areas that have abundant unsurveyed or unenumerated lakes. Very few of the thousands of arctic lakes have been identified by name or number, or characterized by even the most basic limnological parameters (i.e. depth and area) associated with each lake. The objectives for developing this system were threefold. The first objective was that each computer-generated lake identity would be unique and each lake would be retrievable on a geographic basis. The second objective was to combine the identified lakes and computer calculated surface characteristics into a file with sufficient storage space allocated for each lake to accept other data acquired outside this computer system. The final objective was to enable computer manipulation of this file to retrieve lake listings specific to a restricted geographic area and/or lake characteristic(s) defined by a user. This provides the ability to efficiently sort and filter large amounts of lake data for selective classification and reporting of the lakes stored on the file.

A Landsat satellite provides image coverage of the world that is repeated every 18 days. Each Landsat scene covers an area approximately 185 km x 178 km. If the area is not cloud covered, spectral reflectances from the earth's surface are digitally recorded and can be obtained on Computer Compatible Tapes (CCT) for computer manipulation of the data. The Landsat Multispectral Scanner (MSS) records reflectances from 4 spectral bands [band 4 (0.5 to 0.6 μm), band 5 (0.6 to 0.7 μm), band 6 (0.7 to 0.8 μm), and band 7 (0.8 to 1.1 μm)]. These bands are commonly referred to as channels 1 to 4, respectively, in the most recent Landsat data user information (USGS 1979) literature. Band 4 penetrates water to the greatest extent, with up to 80% transmittance through 10 m, while a maximum of < 10% is transmitted through 1 m of water at any near infrared frequency between 0.8 and 1.1 μm in band 7 (Sverdrup 1942). Band 7 elicits the lowest reflectance of water in any of the bands and a high reflectance from vegetation; therefore, the contrast and ability to discriminate between aquatic and terrestrial environments is best in band 7. This has been evident to Landsat users since Landsat inception and has led to studies to identify, define, and classify lakes from these data (Work et al. 1973, Mausel 1974, Tarnocai and Kristof 1975, Boland 1976, Work and Gilmer 1976, Best and Moore 1979, Hoffer 1979).

The significant differences between this and past studies involve two major aspects. The first was to create a computer program that could produce a file that uniquely identifies lakes by geographic location (latitude and longitude) for permanent storage and retrieval of lake information. The second was to design a system that could use off-the-shelf Landsat data to compute accurate map projection lake center positions from Landsat scene coordinates. Only recently has Ground Control Point (GCP) geometric correction been available for Landsat scenes delivered by EROS Data Center in Sioux Falls, South Dakota. Although system capability exists, operational capability is still lacking. The system described in this chapter was the first operating user computer program that required the use of this operational capability for Landsat data (Thormodsgard, personnel communication). The non-availability of GCP corrected data has limited the testing of this system for accuracy. The EROS Data Center and NASA Goddard Space Flight Center have been requested to produce a GCP corrected CCT of a North Slope scene, which in the future should be produced operationally. Upon delivery, this CCT will allow system testing and computer calculation of lake centroids and surface area for accuracy verification.

Methods

A generalized discussion of the methods used to generate the Satellite Lake System (SLS) is provided here to trace system development. Appendix B is a "Satellite Lake System Manual" that describes the system and programs with enough detailed documentation both for the user to operate the system and for the programmer analyst who may wish to make future system modifications. The Landsat Data Users' Handbook (USGS 1979) would also be useful to the user and/or programmer not thoroughly familiar with Landsat data. Users of the SLS need little to no previous experience with computers. The SLS is controlled through a series of key word instructions that are accessed upon entering the programs.

The SLS programs have been designed for and stored in the University of Alaska Honeywell Information System (HIS) 66/20 and are written in FORTRAN and COBOL computer languages. The author developed the initial driver programs that identify discrete lakes and calculate the surface characteristics. A matrix of test data much smaller than a Landsat scene data set was used to test the programs. From this point forward, I directed further system design but did no additional programming. The driver programs were modified by experienced programmers to incorporate efficiency techniques and to enable their use with Landsat CCT data. Morna Seifert has written all COBOL programs used to update and retrieve data from the files created by the driver programs and has documented all programs in the Satellite Lake System Manual (Appendix B).

The SLS is comprised of 2 parts: the identification system and the retrieval system. Flow diagrams for the system as a whole and for each of the 2 parts are in Appendix B.

The identification system uses a Landsat CCT, the driver program LAKEID, and subroutine LCALC to generate a master lake file, with each lake identified by latitude and longitude of its centroid and characterized by area, perimeter, and crenulation calculations. In addition, the identified lakes are plotted on an indexed lake finder output that can be used to verify a lake's shape and size in relation to the geographic context of other surrounding lakes. Another program (UPLAKE) is used to input additional data into the master lake file and to generate a listing of updated lake information in a printout that verifies the master file modification.

The retrieval system program RETRIEV also uses the master lake file to generate the following optional listings: 1) a catalog of all lakes on file in order of descending latitude and longitude; 2) a catalog of all lakes on file sorted by another selected parameter; 3) a list of lakes filtered by limiting a field or fields on 1 or more lake parameters and/or lakes within a specified geographic quadrangle. If a geographic area is specified, the subroutine ARCALC is called to calculate the size of the area in km^2. To be listed as being within the geographic area defined, lake areas must have only their centroid contained within the limiting latitudes and longitudes; however, the entire area of all these lakes, whether completely contained or not, will be summed in the total of aquatic surface areas listed for the specified quadrangle. This must be kept in mind if a comparison of specified geographic area and summed lake areas is made, particularly for a small geographic area containing only part of a large lake.

Discussion

The rectangular area outlined in the 20 July 1979 Landsat Scene No. E-21640-21333 (Figure 65) was processed by the identification system to illustrate some of the Satellite Lake System utility in the vicinity of SLAR-1, 2, and 3 lakes discussed in Chapter II. The quadrangle within the processed area was used for retrieval of lake data from the file created by the identification system. Figure 66 is a 1:250,000 scale USGS topographic map of the area processed and the quadrangle identified for lake information retrieval. Survey data used to produce this map were compiled in 1955; therefore, changes in lake shape and size are to be expected. Figure 67 is a much-reduced

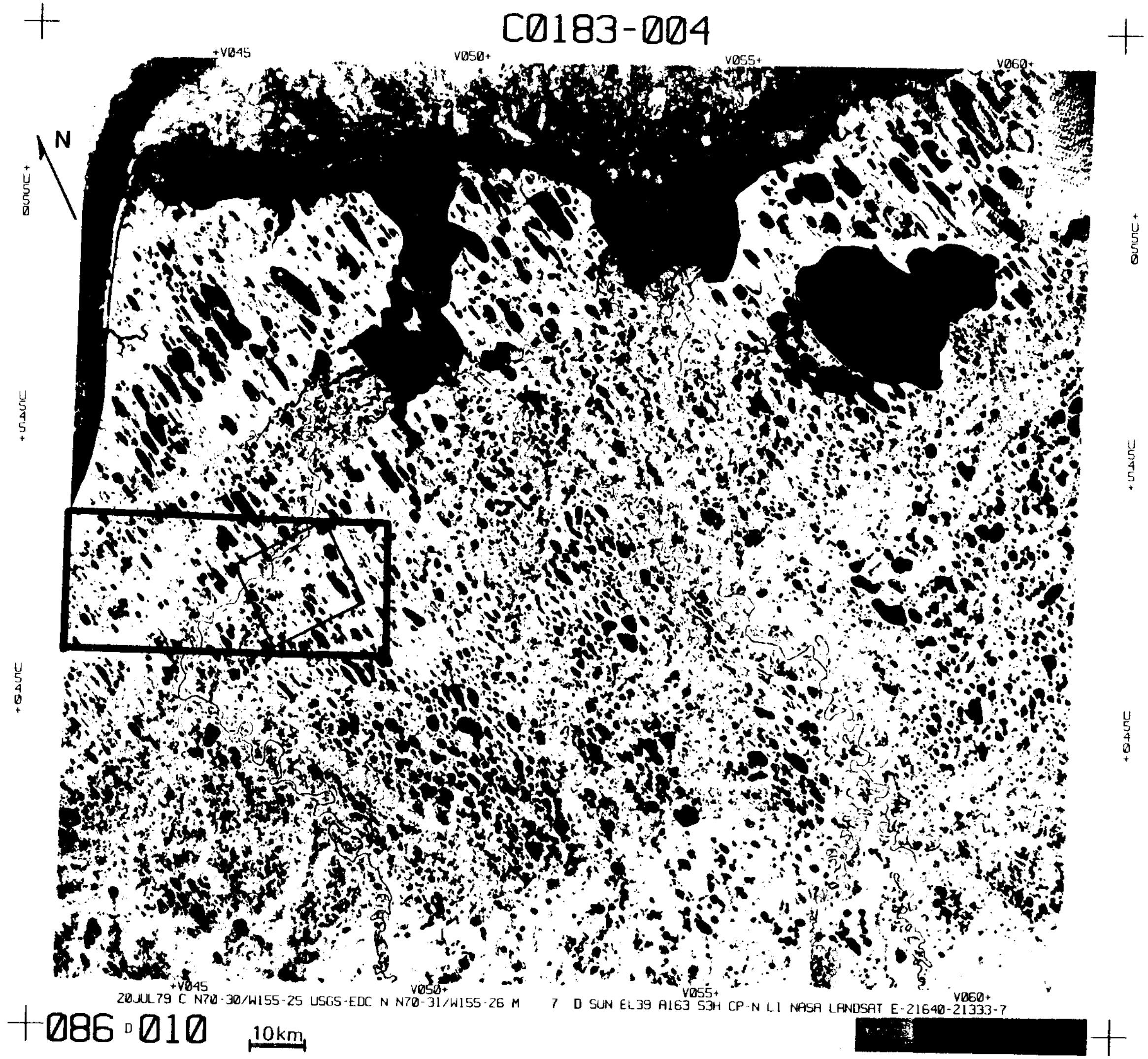


Fig. 65. 20 July 1979 Landsat scene depicting rectangular area processed and inner quadrangle specified for retrieval of lake data.

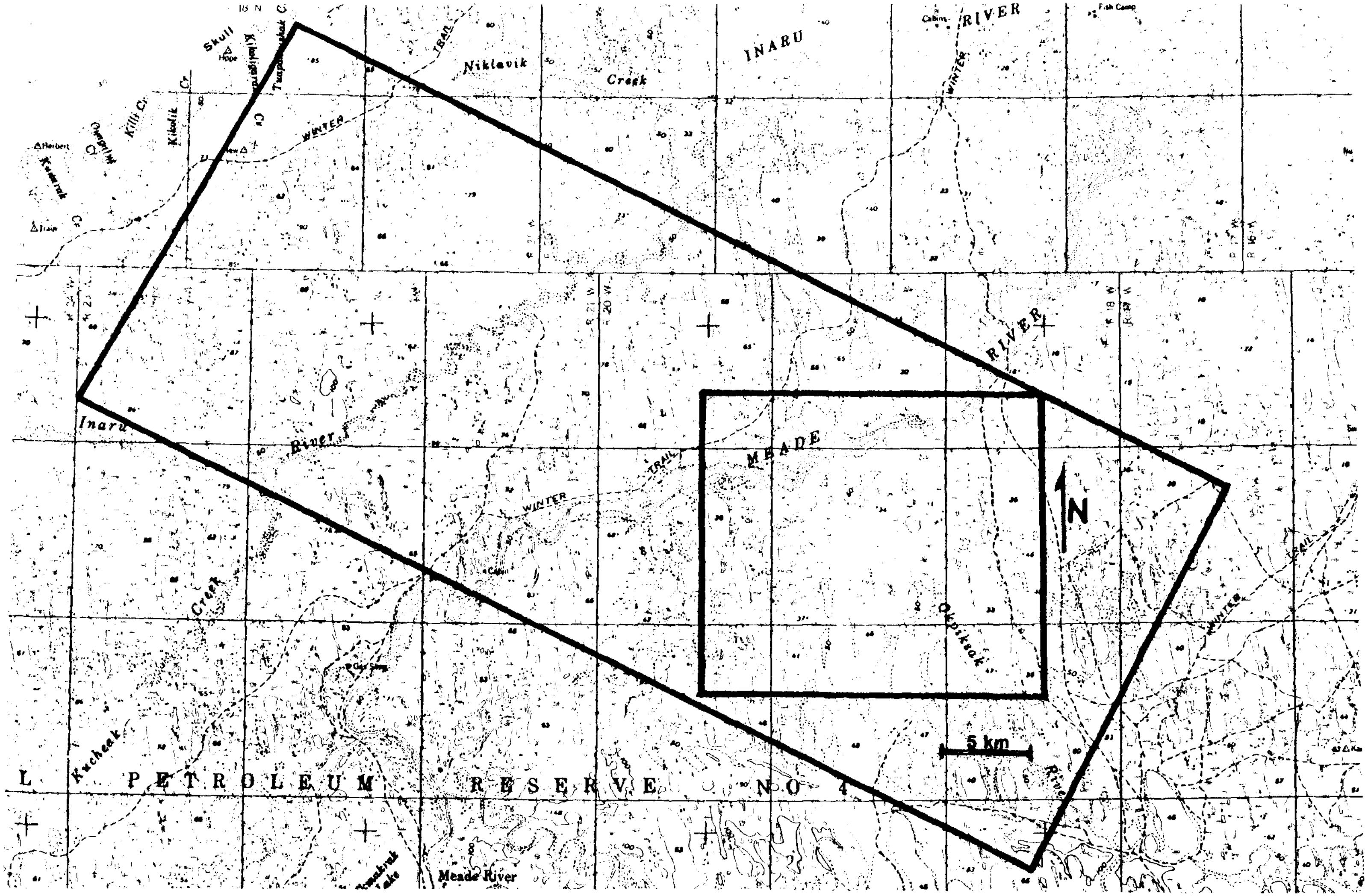


Fig. 66. Map of rectangular area processed and inner quadrangle specified for retrieval of lake data.

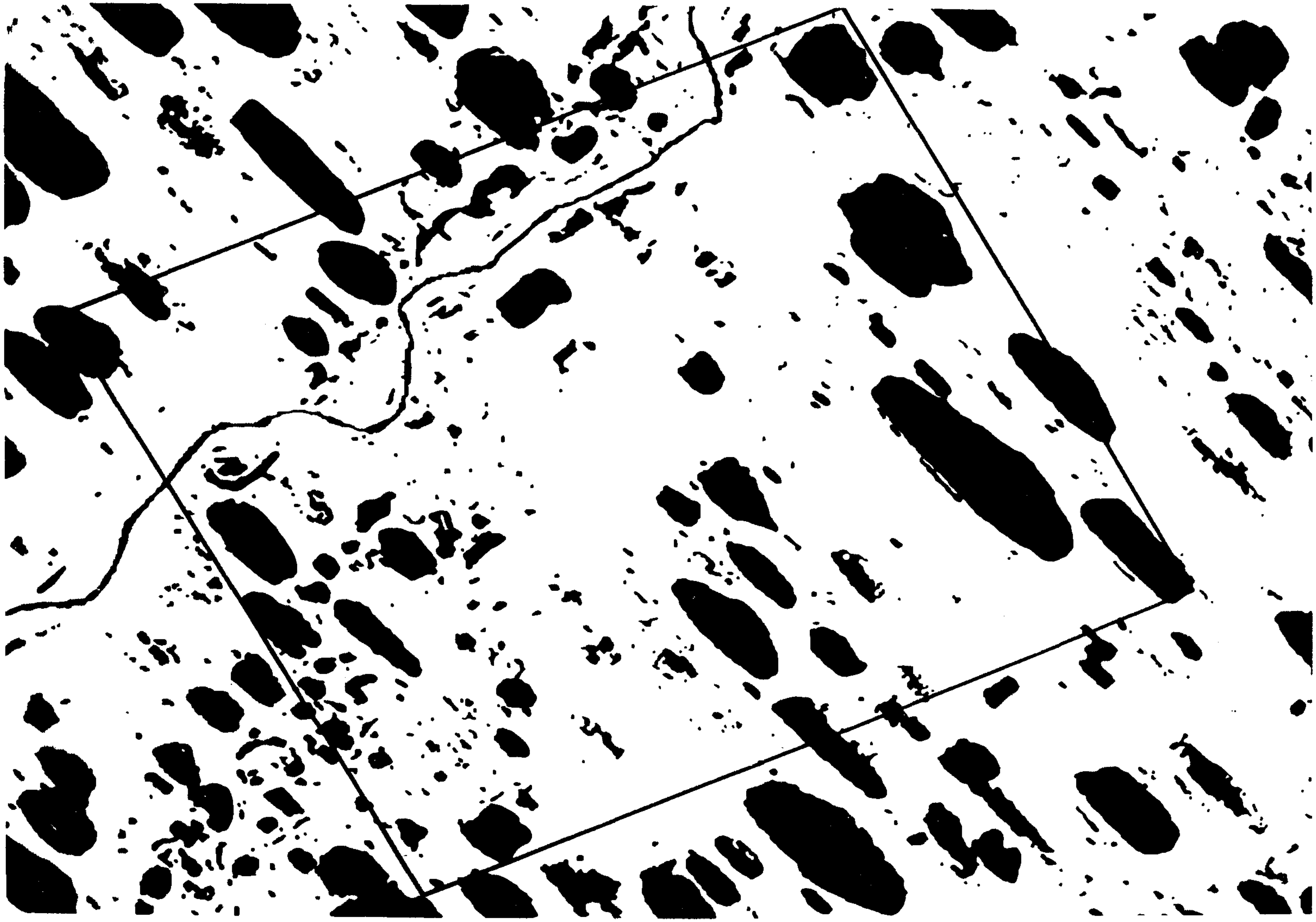


Fig. 67. Lake identification system line printer output depicting eastern half of area processed and inner quadrangle specified for retrieval of lake data.

computer output from the identification system used to verify the lake identification for the eastern half of the area processed. Again, it shows the limits of the area processed and the quadrangle specified for lake information retrieval. The lakes and area are skewed due to lack of geometric correction of this test area. Figure 68 is a 31 July 1977 aerial photograph that is a more recent and accurate portrayal of the water bodies than in the USGS map. The capability for computer identification of surface water is illustrated by comparing Figures 67 and 68. Although the data being compared were collected 2 years apart, and surface water conditions could differ, the similarity between water bodies illustrated is manifest.

Identification System

Lake Identification (Program LAKEID). Lake identification was performed with band 7 data at an intensity threshold of 9. A fully processed CCT in the new EDIPS (EROS Data Center Digital Image Processing System) format was used in the processing. The data contained no GCP's; therefore, no geometric correction has been applied to the scene. Each sample or pixel making up a scene is 57 x 57 m and has an intensity stored for each of the 4 bands. The system has potential for recognizing and identifying lakes as small as 0.5 ha. Landsat MSS resolution is approximately 80 m. Water body identification was performed using a threshold value of 9. All intensities $\leqslant 9$ are water and those > 9 are land. Both the literature (Work and Gilmer 1976) and some simple tests indicate that a threshold of 9 is a good reflectance

Fig. 68. Aerial photograph (31 July 1977) of quadrangle area specified for retrieval of lake data.

value for discriminating between land and water in band 7. The EROS Data Center's General Electric IMAGE 100 System was used to vary this threshold to observe changes in water area discriminated for Alaskan arctic lakes. No change in areas was observed when the reflectance value was changed ± 1, while less than 2% change in area occurred with a change of ± 3 in reflectance values above and below the 9 threshold. Figure 67 illustrates the shape and size of lakes defined using the 9 threshold value. The shape and size of each discrete basin are defined by like numbered sample elements on this printout. Each sample that is identified as land is protrayed as a zero. The printout has been reduced to such an extent that the characters are illegible; therefore, the lake and pond shorelines contained within the quadrangle have been blackened by hand to better define each basin for this illustration.

Utilizing the 9 threshold value, 1,426 separate water bodies were identified that were wholly contained within the area processed. Ponds smaller than 0.5 ha may not be identified and water bodies with less than 80 m separation are merged; thus, the number of computer-identified water bodies within this scene is probably less than what actually exists. This area represents 4.3% of the entire Landsat scene (Figure 65). Approximately 16% of the scene in the upper half consists of very large water bodies, including the Arctic Ocean with embayments and Teshekpuk Lake. The remaining 84% of the scene is the Arctic Coastal Plain, dotted with lakes. If the 4.3% of the scene with 1,426 computer identified water bodies is representative of the remaining land area, the system might identify as many as 28,000 water bodies on the entire terrestrial estate contained within this 1 scene.

Lake Calculations (Subroutine LCALC). Each lake completely contained within the scene area processed has had its centroid (center), area, perimeter, and crenulation calculated and printed out, as exemplified in Table 12. The PIXGEO subroutine is called to convert the Landsat polar coordinates for the lake centroid to latitude and longitude through map projection algorithms. PIXGEO was developed by a number of people cooperating within the USGS Cartography Division at Reston, Virginia, and EROS Data Center Digital Image Processing Group at Sioux Falls, South Dakota. This subroutine and the NASA Goddard Space Flight Center and EROS Data Center systems of geometric correction, through preselected ground control points within each scene, make this lake system unique and particularly useful. A user will be able to obtain an EDIPS corrected CCT that, when fully processed, should be capable of lake basin centroid calculations that have latitude and longitude accuracies within ± 57 m accuracy. This provides a lake data file suitable for geographic retrieval of information at accuracies at or near those of small scale map bases. The original centroid calculation is listed in decimal degrees for latitude and longitude (Table 12). Decimal degrees are converted to degrees and decimal minutes for lake data retrieval, but the decimal degrees to 5 places for both latitude and longitude provide the unique identity for each lake.

Table 12. Identification system output exemplifying listing of lakes and computer calculated parameters.

LATITUDE	LONGITUDE	INDEX	AREA KM SQ.	PERIMETER KM	CRENULATION	CENTROID M	N
70.76377N	157.64985W	1142	0.01300			1717.0	265.5
70.76081N	157.63387W	1148	0.00975			1717.7	277.3
70.77462N	157.72085W	1152	0.00325			1718.0	215.0
70.72524N	157.41567W	1153	0.00650			1718.0	434.5
70.66118N	157.02657W	1157	0.00325			1718.0	716.0
70.57409N	156.50927W	1159	0.00325			1718.0	1093.0
70.58568N	156.57850W	786	8.55400	19.899	1.919	1718.3	1042.5
70.63822N	156.89267W	1084	0.47775	4.993	2.038	1719.1	813.8
70.63548N	156.87974W	1113	0.40300	3.255	1.447	1720.1	823.7
70.67501N	157.11084W	1132	0.09100	1.238	1.158	1718.3	655.0
70.79026N	157.82583W	1135	0.15925	2.255	1.594	1720.1	140.8
70.64688N	156.94201W	1141	0.09750	1.120	1.012	1718.4	777.6
70.62266N	156.79619W	1144	0.02925			1718.0	883.5
70.61386N	156.75814W	1150	0.10075	2.131	1.894	1722.2	913.3
70.69303N	157.21914W	1154	0.00975			1718.0	576.5
70.68540N	157.17281W	1155	0.00650			1718.0	610.0
70.67250N	157.09568W	1156	0.01625			1718.3	666.0
70.65871N	157.01889W	1158	0.04225			1720.1	722.6
70.78245N	157.77144W	1160	0.00650			1718.5	179.0
70.58967N	156.60088W	1162	0.00325			1718.0	1026.0
70.75958N	157.63273W	1163	0.00650			1719.5	279.0
70.68334N	157.16382W	1164	0.00325			1719.0	617.0
70.61701N	156.76767W	1165	0.00650			1719.5	905.0
70.55411N	156.39918W	1166	0.00975			1720.0	1174.7
70.76049N	157.64012W	1167	0.00325			1720.0	274.0
70.72504N	157.42822W	1168	0.05200			1721.9	427.4
70.69006N	157.21321W	1169	0.03250			1721.5	582.5
70.61378N	156.75192W	1172	0.00650			1720.5	917.0
70.55731N	156.41785W	1174	0.00325			1720.0	1161.0
70.76194N	157.65436W	1177	0.01300			1721.5	264.5
70.68319N	157.17212W	1178	0.00975			1721.7	612.3
70.55230N	156.39365W	1179	0.00650			1721.5	1179.5
70.77099N	157.71593W	1184	0.00325			1723.0	221.0
70.72600N	157.43784W	1186	0.00975			1723.0	421.0
70.67056N	157.10034W	1189	0.00325			1723.0	665.0
70.75806N	157.64028W	1192	0.00975			1724.3	276.0
70.61947N	156.80157W	1193	0.01950			1725.2	883.2
70.71785N	157.39604W	1196	0.00975			1725.3	452.3
70.71627N	157.38518W	1197	0.00325			1725.0	460.0
70.61093N	156.75029W	1200	0.00650			1725.0	920.5

NOTE: PERIMETER IS CALCULATED ONLY FOR LAKES WITH AREAS GREATER THAN .09.
ALL CALCULATIONS STORED FOR NORTH, SOUTH BORDER LAKES

Area is the second most useful lake parameter calculated. The area is calculated to 5 places for accurate summation of the smallest resolution cell, being the 57 x 57 m sample, with an area of .00325 km^2. Lake area is an easy, inexpensive, and useful parameter to calculate.

Perimeter is calculated through the rigorous and time-consuming process of following the perimeter samples around the computer generated lake shore. The perimeter is listed (Table 12) to 3 decimal places. Removing this calculation from the program might save a significant amount of computer time, but this has not been tested. Perimeter and centroid calculations in lakes less than about .05 km^2 area are erroneous and have been omitted.

Crenulation is calculated from area and perimeter values to provide an index of shoreline development or how scalloped versus smooth and circular the lakeshore is. A value of 1.000 is the idealized smooth shoreline of a circular lake of equal area (see subroutine LCALC). The index value increases from 1.000 as the shoreline crenulation increases. Best and Moore (1979) have also developed a shoreline development index interpreted from Landsat MSS imagery.

Additional lake surface characteristics, such as length and azimuths of major and minor axes, might be added to computer calculations in the future; however, storage space and computer cost have limited this system to centroid, area, perimeter, and crenulation. Perimeter and crenulation are not particularly important lake criteria but show the potential for calculating a variety of lake surface characteristics from computer-compatible Landsat data.

Updating Lake File Information (Program UPLAKE)

The master lake file test area was updated with additional information for 3 lakes within the quadrangle specified for retrieval. These lakes were SLAR-1, 2, and 3 described in Chapter II. The updating procedure added data (e.g. lake name, maximum depth, area of free water below ice, fish, vegetation, conductivity, etc.) to the file. Tables 13 and 14 illustrate the difference between computer retrievals from the file before and after updating.

Retrieval System

Seven variations of lake retrieval requests (Tables 13-17A,B&C) illustrate part of the retrieval system capabilities. Computer listings of lakes on file can be generated by requesting a catalog of all lakes or by selective retrieval of lakes within a specified geographic quadrangle or of lakes with specified characteristics. The tables provide examples of computer listings retrieved from a user defined quadrangle and by selectively filtering the file with the lake parameters: depth, presence of inlets and outlets, and surface area. A quadrangle representing about 1% of the total area within the scene was identified for retrieval that includes SLAR-1, 2, and 3 lakes. This quadrangle is about 286 km^2 and is shown in Figures 65, 66, 67, and 68 relative to the 1,370 km^2 area that was processed to create the lake file. This quadrangle was chosen primarily because of the verification data that existed for SLAR-1, 2, and 3 lakes, but the area is representative of

Table 13. Retrieval system output with quadrangle and lakes > 2.0 km^2 in area specified prior to updating information for lakes SLAR-1, SLAR-2, and SLAR-3.

```
                              SPECIFIED GEOGRAPHIC AREA DETAIL LISTING
                                              10/20/80
QUAD  LAT.       LONG.        NAME         MAX.- DEPTH   FREE WATER BELOW ICE  VERIFIED              *****LANDSAT COMPUTER CALCULATED*****
      DEG. MIN.  DEG. MIN.                 (M)  - DATE   AREA(SQ KM) - DATE    AREA(SQ KM)-DATE     AREA(SQ KM) PERIMETER(KM) CRENULATION
*****************************************************************************************************************************************
      CLASS.        INLET  OUTLET   FISH - - -  - - - - - - - - - -DATE         EMERGENT VEGETATION - - - - - - - - - - - PERCENT - - -DATE
*****************************************************************************************************************************************
           CONDUCTIVITY  SUBSTRATE        ACTIVITY           VECTOR    SCENE      REFERENCES   LAKE NO.    SAMPLE    LINE
*****************************************************************************************************************************************

1MEA  70 41.43N 156 33.60W                                                                       2.92500         7.175         1.183

                                                                      21640213337      N      (0)064      959     1530

1MEA  70 38.92N 156 59.28W                                                                       2.45050         6.648         1.198

                                                                      21640213337      N      (1)073      749     1728
1MEA  70 38.82N 156 34.40W                                                                       5.73950         9.781         1.152

                                                                      21640213337      N      (0)382      991     1610
1MEA  70 35.14N 156 34.71W                                                                       8.55400        19.899         1.919

                                                                      21640213337      N      (0)786     1042     1718

USER DEFINED GEOGRAPHIC AREA          285.61442 SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA        19.66900 SQ.KM.
```

Table 14. Retrieval system output with quadrangle and lakes > 2.0 km^2 in area specified after updating information for lakes SLAR-1, SLAR-2, and SLAR-3.

```
                                          SPECIFIED GEOGRAPHIC AREA DETAIL LISTING
                                                        10/20/80
QUAD  LAT.        LONG.        NAME          MAX.- DEPTH   FREE WATER BELOW ICE   VERIFIED             *****LANDSAT COMPUTER CALCULATED*****
      DEG. MIN. DEG. MIN.                    (M) - DATE    AREA(SQ KM) - DATE     AREA(SQ KM)-DATE    AREA(SQ KM) PERIMETER(KM) CRENULATION
**********************************************************************************************************************************************
     CLASS.       INLET  OUTLET  FISH - - -  - - - - - - - - -DATE        EMERGENT VEGETATION - - - - - - - - - - PERCENT - - -DATE
**********************************************************************************************************************************************
          CONDUCTIVITY   SUBSTRATE       ACTIVITY              VECTOR     SCENE      REFERENCES   LAKE NO.   SAMPLE   LINE
**********************************************************************************************************************************************

1MEA  70 41.43N 156 33.60W  SLAR 1        2.2  10979    1.81000     150579   2.70000     877    2.92500         7.175        1.183
     LT UM           N    N                                                                                                   10979
                          UM                                      21640213337    N      (0)064      959   1530

1MEA  70 38.92N 156 59.28W                                                                      2.45050         6.648        1.198


                                                                  21640213337    N      (1)073      749   1728
1MEA  70 38.82N 156 34.40W  SLAR 2        1.8  10979                150579   5.57000     877    5.73950         9.781        1.152
     LT UM           N    N                              10979                                                                10979
              300         UM                                      21640213337    N      (0)382      991   1610
1MEA  70 35.14N 156 34.71W  SLAR 3        1.9  10979                150579   8.60000     877    8.55400        19.899        1.919
     LT UM           Y    Y
              123         UM                                      21640213337    N      (0)786     1042   1718

USER DEFINED GEOGRAPHIC AREA          285.61442 SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA          19.66900 SQ.KM.
```

Table 15. Retrieval system output with quadrangle and lakes > 2.5 km^2 in area specified.

```
                                    SPECIFIED GEOGRAPHIC AREA DETAIL LISTING
                                                  10/20/80
QUAD  LAT.       LONG.        NAME         MAX.- DEPTH   FREE WATER BELOW ICE   VERIFIED               *****LANDSAT COMPUTER CALCULATED*****
      DEG. MIN. DEG. MIN.                  (M) - DATE    AREA(SQ KM) - DATE     AREA(SQ KM)-DATE   AREA(SQ KM) PERIMETER(KM) CRENULATION
**************************************************************************************************************************************
     CLASS.       INLET  OUTLET    FISH - - -  - - - - - - - - - -DATE         EMERGENT VEGETATION - - - - - - - - - - - PERCENT - - -DATE
**************************************************************************************************************************************
            CONDUCTIVITY   SUBSTRATE        ACTIVITY              VECTOR     SCENE      REFERENCES    LAKE NO.    SAMPLE    LINE
**************************************************************************************************************************************

1MEA  70 41.43N 156 33.60W  SLAR 1        2.2  10979    1.81000     150579    2.70000      877    2.92500        7.175          1.183
     LT UM            N    N                                                                                                    10979
                           UM                                               21640213337     N      (0)064     959    1530

1MEA  70 38.82N 156 34.40W  SLAR 2        1.8  10979                150579    5.57000      877    5.73950        9.781          1.152
     LT UM            N    N                                    10979                                                           10979
                300       UM                                                21640213337     N      (0)382     991    1610
1MEA  70 35.14N 156 34.71W  SLAR 3        1.9  10979                150579    8.60000      877    8.55400       19.899          1.919
     LT UM            Y    Y
                123       UM                                                21640213337     N      (0)786    1042    1718

USER DEFINED GEOGRAPHIC AREA          285.61442 SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA        17.21850 SQ.KM.
```

Table 16. Retrieval system output with quadrangle and lakes > 1.0 km^2 in area specified.

```
                                    SPECIFIED GEOGRAPHIC AREA DETAIL LISTING

                                                 10/20/80

QUAD  LAT.      LONG.         NAME          MAX.- DEPTH    FREE WATER BELOW ICE  VERIFIED           *****LANDSAT COMPUTER CALCULATED*****
      DFG. MIN. DEG. MIN.                    (M) - DATE    AREA(SQ KM) - DATE    AREA(SQ KM)-DATE   AREA(SQ KM) PERIMETER(KM) CRENULATION
*************************************************************************************************************************************
    CLASS.        INLET  OUTLET   FISH - - -  - - - - - - - - - -DATE         EMERGENT VEGETATION - - - - - - - - - - PERCENT - - -DATF
*************************************************************************************************************************************
          CONDUCTIVITY   SUBSTRATE        ACTIVITY              VECTOR     SCENE      REFERENCES    LAKE NO.    SAMPLE   LINE
*************************************************************************************************************************************


1MEA   70 41.81N 156 49.26W                                                                          1.30650        10.691         2.639


                                                                      21640213337      N      (0)359      803   1595


1MEA   70 41.60N 156 51.37W                                                                          1.88500         5.734         1.178


                                                                      21640213337      N      (0)528      786   1612
1MEA   70 41.43N 156 33.60W  SLAR 1          2.2  10979     1.81000     150579    2.70000      877    2.92500         7.175         1.183
     IT UM             N    N                                                                                                     10979
                            UM                                        21640213337      N      (0)064      959   1530
1MEA   70 40.60N 156 47.16W                                                                          1.43325         4.698         1.107


                                                                      21640213337      N      (0)592      841   1620
1MEA   70 38.92N 156 59.28W                                                                          2.45050         6.648         1.198


                                                                      21640213337      N      (1)073      749   1728
1MEA   70 38.82N 156 34.40W  SLAR 2          1.8  10979                 150579    5.57000      877    5.73950         9.781         1.152
     IT UM             N    N                            10979                                                                    10979
              300           UM                                        21640213337      N      (0)382      991   1610
1MEA   70 38.21N 156 54.88W                                                                          1.29025         5.235         1.300


                                                                      21640213337      N      (1)112      802   1727

1MEA   70 37.12N 156 43.14W                                                                          1.70625         5.980         1.291


                                                                      21640213337      N      (0)970      931   1702
1MEA   70 36.04N 156 43.78W                                                                          1.15375         5.239         1.376


                                                                      21640213337      N      (1)134      941   1736
1MEA   70 35.14N 156 34.71W  SLAR 3          1.9  10979                 150579    8.60000      877    8.55400        19.899         1.919
     IT UM             Y    Y
              123           UM                                        21640213337      N      (0)786     1042   1718

USER DEFINED GEOGRAPHIC AREA           285.61442 SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA         28.44400 SQ.KM.
```

Table 17. Retrieval system output for lakes: A) > 1.0 m deep; B) > 2.0 m deep; C) that have an inlet and outlet.

A

```
QUAD  LAT.       LONG.        NAME          MAX.- DEPTH   FREE WATER BELOW ICE  VERIFIED           *****LANDSAT COMPUTER CALCULATED*****
      DEG. MIN. DEG. MIN.                   (M) - DATE    AREA(SQ KM) - DATE    AREA(SQ KM)-DATE  AREA(SQ KM) PERIMETER(KM) CRENULATION
**************************************************************************************************************************************
   CLASS.      INLET  OUTLET   FISH - - -  - - - - - - - - -DATE      EMERGENT VEGETATION - - - - - - - - - - PERCENT - - -DATE
**************************************************************************************************************************************
         CONDUCTIVITY   SUBSTRATE       ACTIVITY             VECTOR    SCENE     REFERENCES   LAKE NO.   SAMPLE   LINE
**************************************************************************************************************************************

1MEA  70 41.43N 156 33.60W  SLAR 1         2.2  10979     1.81000    150579    2.70000     877    2.92500        7.175         1.183
   LT UM            N    N                                                                                                    10979
                         UM                                           21640213337     N       (0)064      959   1530

1MEA  70 38.82N 156 34.40W  SLAR 2         1.8  10979                150579    5.57000     877    5.73950        9.781         1.152
   LT UM            N    N                                10979                                                               10979
         300             UM                                           21640213337     N       (0)382      991   1610
1MEA  70 35.14N 156 34.71W  SLAR 3         1.9  10979                150579    8.60000     877    8.55400       19.899         1.919
   LT UM            Y    Y
         123             UM                                           21640213337     N       (0)786     1042   1718

USER DEFINED GEOGRAPHIC AREA         000000     SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA        17.21850 SQ.KM.
```

B

```
QUAD  LAT.       LONG.        NAME          MAX.- DEPTH   FREE WATER BELOW ICE  VERIFIED           *****LANDSAT COMPUTER CALCULATED*****
      DEG. MIN. DEG. MIN.                   (M) - DATE    AREA(SQ KM) - DATE    AREA(SQ KM)-DATE  AREA(SQ KM) PERIMETER(KM) CRENULATION
**************************************************************************************************************************************
   CLASS.      INLET  OUTLET   FISH - - -  - - - - - - - - -DATE      EMERGENT VEGETATION - - - - - - - - - - PERCENT - - -DATE
**************************************************************************************************************************************
         CONDUCTIVITY   SUBSTRATE       ACTIVITY             VECTOR    SCENE     REFERENCES   LAKE NO.   SAMPLE   LINE
**************************************************************************************************************************************

1MEA  70 41.43N 156 33.60W  SLAR 1         2.2  10979     1.81000    150579    2.70000     877    2.92500        7.175         1.183
   LT UM            N    N                                                                                                    10979
                         UM                                           21640213337     N       (0)064      959   1530


USER DEFINED GEOGRAPHIC AREA         000000     SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA        2.92500 SQ.KM.
```

C

```
                                  SPECIFIED GEOGRAPHIC AREA DETAIL LISTING
                                                10/20/80
QUAD  LAT.       LONG.        NAME          MAX.- DEPTH   FREE WATER BELOW ICE  VERIFIED           *****LANDSAT COMPUTER CALCULATED*****
      DEG. MIN. DEG. MIN.                   (M) - DATE    AREA(SQ KM) - DATE    AREA(SQ KM)-DATE  AREA(SQ KM) PERIMETER(KM) CRENULATION
**************************************************************************************************************************************
   CLASS.      INLET  OUTLET   FISH - - -  - - - - - - - - -DATE      EMERGENT VEGETATION - - - - - - - - - - PERCENT - - -DATE
**************************************************************************************************************************************
         CONDUCTIVITY   SUBSTRATE       ACTIVITY             VECTOR    SCENE     REFERENCES   LAKE NO.   SAMPLE   LINE
**************************************************************************************************************************************

1MEA  70 35.14N 156 34.71W  SLAR 3         1.9  10979                150579    8.60000     877    8.55400       19.899         1.919
   LT UM            Y    Y
         123             UM                                           21640213337     N       (0)786     1042   1718


USER DEFINED GEOGRAPHIC AREA         285.61442 SQ.KM.
TOTAL AREA OF LAKES WHOSE CENTER IS WITHIN DEFINED AREA        8.55400 SQ.KM.
```

the Arctic Coastal Plain and contains riverine as well as lacustrine and palustrine environments.

Catalog. An example of catalog retrieval is not included here, because all 1,426 lakes on the master file would have been listed after being sorted by one of the following: latitude and longitude, maximum depth, computer calculated surface area, free water area beneath ice, % vegetation cover, conductivity, or name.

Geographic Quadrangle. A geographic quadrangle was identified to limit consideration of the 1,426 lakes in the file to a specific area of interest by requesting the latitude and longitude of the northeast and southwest corners in degrees and minutes accurate to 1 decimal place. The subroutine ARCALC calculates the area defined and prints the area at the end of requested output as the "user defined geographic area" (Tables 13, 14, 15, 16, and 17C). The computer-calculated area was 285.61442 km^2. The quadrangle was not specified for 2 of the 3 outputs included in Table 17. When not specified, the area shown is 0 km^2 (Tables 17A and B). During a retrieval run, the quadrangle was specified with no further lake filtering parameters. This request listed and summed all water basins within the 285.6 km^2 area. The listing is not included here because of its size, but 252 lakes with a combined area of 43 km^2 were listed. The percentage of water over this terrestrial estate was 15% of the total land area as calculated from this computer generated listing.

Filtering by Parameters in the File. Comparator (>, =, <) qualification of selected parameters may be used to limit lake retrieval with or without specifying a specific geographic locality. The lakes which have not been updated will have zeros filling all fields except those calculated by the computer identification system. In this example, the only lakes with non-computer generated data in the lake file were lakes SLAR-1, 2, and 3; therefore, if a ">" comparator was used to limit parameters such as depth, the only lakes with non-zero data in the depth file were the SLAR lakes. Examples of this are Parts A and B of Table 17. Lakes not updated with lake depth data were considered 0 m deep; therefore, when lakes > 1.0 m (Table 17A) and > 2.0 m (Table 17B) were requested, only SLAR lakes were considered. Since all 3 SLAR lakes were > 1.0 m, all 3 were listed in Table 17A. Only SLAR-1, which is 2.2 m deep, was listed when the limit specified was > 2.0 m depth. SLAR-3 was the only SLAR lake with an inlet or outlet and was listed (Table 17C) when lakes with inlets and outlets were requested.

The parameters that may be used in combination for limiting lake retrieval are: geographic quadrangle; lake surface area; free water area below ice; conductivity; presence or absence of fish; presence, absence, or % area of vegetation; and presence or absence of inlets and/or outlets. Comparators are used in combination with a limiting value or with yes or no qualifications to limit the properties listed above for filtering out lakes of no interest. Lakes of interest are then listed in computer-formatted tables, as shown.

Computer-calculated lake areas within the specified quadrangle provide a good example for use of the comparator with lake surface areas of 1.0, 2.0, and 2.5 km^2. Tables 16, 14, and 15 are retrieval listings that were limited to only those lakes with surface areas > 1.0, > 2.0, and > 2.5 km^2, respectively, within the quadrangle. There were 10 lakes listed with areas > 1.0 km^2 in Table 16. Four lakes had areas > 2.0 km^2 in Table 14. The SLAR lakes were the largest 3 lakes in the area. The > 2.5 km^2 area (Table 15) was selected to be less than the 2.925 km^2 area for the smallest of SLAR lakes (SLAR-1) but slightly larger than the next smaller lake area (2.45050 km^2) within the quadrangle. This left only SLAR-1, 2, and 3 lakes with both computer-calculated and auxiliary updated data.

Although usable in its present form, this computer lake system is not complete and can be refined in the future to provide more utility with greater simplicity if time, money, and interest prevail. Three areas need additional attention. A method must be devised to merge master files from multiple overlapping Landsat scenes to enable extension of geographic coverage without duplication of lakes in the overlapping areas. Secondly, an algorithm should be developed to ease the updating lake data entry so that specific lakes on the lake file can be accessed and verified with a minimum of centroid position accuracy, a maximum of data entry ease, and a minimum potential for lake identity error. Finally, spectral thresholds used to discriminate between water and land must be investigated further, and verification of computer generated product accuracy, utility, and cost must be completed.

Summary

A computer lake system was developed that uses computer compatible Landsat data to create a lake information file uniquely characterizing each lake in the file. The computer-calculated latitude and longitude of the centroid for each lake provide a lake file with a geographic data base from which lakes can be retrieved for a defined area. Computer calculations of surface area, perimeter, and crenulation further characterize each lake. The lake file provides storage for additional information obtained about a lake from other sources. Retrieval of lakes on file can be accomplished through sorting and sieving (filtering) functions defined by parameters of interest and values limited by comparators (>, =, and <). When a geographic area containing lakes of interest is specified, the user-defined area is calculated and printed at the end of the listing. The sum of all lake surface areas in the listing is also printed for comparison with the geographic area in which they exist.

This system has several potential uses. It could be used to consolidate aquatic data for dynamic retrieval. This can supplement or replace conventional means of lake data management and analysis. The system provides worldwide capability for rapid survey of lakes in relatively flat terrain and for monitoring their changes in time. Finally, it provides the capability for lake classification through sorting and filtering functions applied to the various lake parameters on file.

CHAPTER V

SUMMARY

REGIONAL LAKE INVENTORY

Three different SLAR signal returns provided depth information on images of the lakes studied. A bright image was obtained from areas where there was fresh water beneath the ice cover in a lake $\leq$ 4 m deep. The occurrence of columnar gas bubbles in ice covering shallow areas provided a mechanism for reflecting or back-scattering the SLAR signal to give the bright image common to the lakes studied but uncommon to nonarctic lakes. A dark image was obtained from a lake that was either frozen to the bottom or had water beneath the ice with a salinity > $2°/_{oo}$. Here little if any signal was reflected at the ice/water interface. Intermediate gray-tones occurred in a lake image where water beneath the ice was > $1°/_{oo}$ and $\leq 2°/_{oo}$ salinity or was in a lake area > 4 m deep. Lake areas > 4 m deep had an ice cover containing few columnar bubbles to back-scatter or reflect the SLAR signal effectively, while shallow lakes with high salinity had bubbles, but brine within the ice must attenuate much of the SLAR signal near the ice/water interface. Some potential exists for discriminating between gray-tones caused by increasing salinity and those produced by > 4 m lake depths, but SLAR image blemishes and resolution complicate this problem.

The ice cover/lake bottom contact zone can be interpreted from the SLAR image of a lake. This interpretation plus ice cover thickness for the image date provide an approximation of the lake isobath at that ice thickness. Sequential SLAR images over a lake basin in conjunction with ice thickness information over the winter ice growth season can be used to estimate isobaths down to the limit of maximum ice growth. April was determined to be the optimum month to acquire SLAR images of Alaskan arctic lakes for winter water assessment. April 1980 SLAR acquired over most of the National Petroleum Reserve in Alaska are being used to define depth contours and winter water sources at near maximum ice thickness.

The SLAR image determination of lake bathymetry must be coupled with the ability to assess some lake constituents and resources associated with that bathymetry to become a significant regional inventory/assessment tool.

Limnological surveys of the 9 study lakes showed that wind and marine influence had significant climatic effect, increasing salinities, suspended sediment loads and light attenuation in lakes toward the seaward end of the study area. The maximum depths of study lakes were deeper in the middle (12 m) and at the southern (7 m) end of the transect than at the northern end (3 m). Variations in algal biomass, summer and winter temperatures, winter dissolved oxygen, and ice cover measurements were also related to changes in climate across the study area.

Many of the constituents and resources sampled, that changed with water depth, changed because of physical factors such as wind generated waves and ice accretion that affect the shallow (< 3 m) lake environments most significantly. Wind-generated wave mixing in shallow water causes sorting of benthic substrate materials, changes in water column suspended sediments and light attenuation, possible nutrient replenishment from resuspended sediments, and quantitative shifts in benthic versus water column chlorophyll *a* and primary production measurements. Shallow basins and/or shoals within deep basins are the most severely affected by wave action.

Ice accretion causes a percentage reduction in free water volume that is inversely proportional to lake depth. In shallow lakes ice accretion causes rapid increases in specific conductance, freezing of shallow substrates and their benthic inhabitants, increases in columnar gas bubbles in ice cover, depletion of dissolved oxygen, limited fish and zooplankton habitats, and near freezing water temperatures. Ice limits the lake depth range of benthic invertebrate species intolerant of frozen habitat. Overwintering fish require lake depths greater than maximum ice thickness and are rarely found in lakes < 3 m deep. Most of the summer's heat is used to melt thick ice cover, leaving little to heat the water column of deep lakes. Ice on shallow basins melts early, allowing sediment and water to attain very warm summer temperatures. Emergent vascular vegetation species are limited to specific ranges in water depth. Waterfowl utilize aquatic resources that occur in specific shallow ranges of water depth; hence, water depth information can be used to help define waterfowl habitat. Water depth information can also be used to help identify lakes for winter water supplies and/or surface uses, such as airstrips or other vehicle travel.

These results show that bathymetry is a major factor in predicting aquatic resources associated with Alaskan arctic lakes, and indicate that bathymetry is the best single parameter that can be used to classify and define the resource potential of all arctic lake habitats.

The voluminous data that could be generated with the regional inventory tools summarized above pose a potential data management problem. A proposed solution I developed is a computer lake system that uses computer-compatible Landsat data to create a lake information file uniquely characterizing each lake in the file. The accumulated computer-calculated latitude and longitude of the centroid for each lake provide a data file catalog from which lakes can be retrieved for a user specified area. Computer calculations of surface area, perimeter, and crenulation further characterize each lake. The lake file provides storage for additional information obtained about a lake from other sources such as the SLAR images and field notes.

The computer lake system could be used to: consolidate aquatic data, supplement or replace conventional means of lake data management and analysis, provide worldwide capability for rapid survey of lakes in relatively flat terrain, and monitor lake changes in time. Finally, it provides the capability for lake classification through sorting and filtering functions applied to the various lake parameters on file.

SLAR images can be used to determine some lake bathymetry while digital Landsat data can be used to inventory surface features and manage all lake data for classification and retrieval of lake information through a semi-automated computer lake system. These investigations have demonstrated the potential for using regional remote-sensing tools coupled with lake depth/resource and constituent associations to better inventory, assess, and manage Arctic Coastal Plain aquatic resources.

FUTURE WORK

The limnological investigations conducted for the purpose of this dissertation concentrated on some baseline sampling of many constituents rather than extensive sampling of a few. Many of the water depth/constituent relationships required further study to define, refine, or quantify the associations highlighted here. Nutrient, chlorophyll *a* and primary production relationships measured during the summer should be investigated throughout the annual cycle, but ice cover and cold temperatures make this a difficult task. Further winter investigation of dissolved gas depletion from lake waters and evolution and incorporation of gases into the ice cover should be completed for lake waters of different depth. SLAR images must be compared with presence and absence of columnar gas bubbles in ice to refine the interpretation of SLAR gray-tones at lake depths near 4 m.

Additional ice thicknesses will have to be measured to extend SLAR surveys for regional determinations of lake bathymetry. Aquatic ecosystem controls caused by local conditions of ice thickness and snow depth, regional climate, and specific ranges of water depth can be refined further when and if additional scanning radar (i.e. SLAR or SAR) surveys can be acquired and coupled with lake verification data.

Mechanisms for the interaction of a SLAR signal with snow, ice, water, and soil interfaces have been hypothesized for the various signal returns observed. The physics of SLAR signal interaction with the interface types found in Alaskan arctic lakes needs to be investigated more thoroughly to remove any doubt about the mechanisms of SLAR signal interaction. The number and types of gas bubbles in ice cover over lake depths > 4 and < 4 m should be investigated more thoroughly and compared with SLAR images to refine the ability to determine lake depths greater than maximum ice thickness (2 m).

Although the computer lake system is usable in its present form, it is not complete and can be refined to provide more utility with greater simplicity with some additional effort. In addition, spectral thresholds used to discriminate between water and land must be investigated further, and verification of computer generated product accuracy, utility, and cost must be completed. This can be accomplished by processing some Alaskan arctic areas with summer Landsat scene data and by verifying the computer generated lake file products with recent aerial photographs and lake survey data.

REFERENCES CITED

Alaska Department of Fish and Game, Sport Fish Division, Fairbanks, Alaska. 1977. Fishery survey of major watershed headwaters of NPR-A. 21 p.

Alaska Water Quality Management Planning Program. 1977. Transportation corridors/water quality problem description. Alaska Dept. of Environ. Cons. 106 p.

Alexander, V., J. Mellor, and R. Barsdate. 1978. Suspended sediments and related limnology of an alpine lake system, third year report. Institute of Marine Science, Univ. Alaska. 39 p.

Andreyev, V. N. 1979. Botanical observations in Alaska. U.S. Army Cold Regions Res. and Eng. Lab., Hanover, N.H. Translation.

Arcone, S. A., A. J. Delaney, and P. V. Sellmann. 1979. Detection of arctic water supplies with geophysical techniques. U.S. Army Cold Regions Res. and Eng. Lab., Hanover, N.H. Rept. 79-15, 30 p.

Bergman, R. D., R. L. Howard, K. F. Abraham, and M. W. Weller. 1977. Water birds and their wetland resources in relation to oil development at Storkersen Point, Alaska. U.S. Fish and Wildlife Service Res. Publ. 129, 38 p.

Best, R. G., and D. G. Moore. 1979. Landsat interpretation of prairie lakes and wetlands of eastern South Dakota. Proceedings 5th Annual Pecora Symposium on satellite hydrology. June 1979.

Bilello, M. A. 1964. Ice thickness observations, North American arctic and subarctic, 1961-62. U.S. Army Cold Regions Res. and Eng. Lab., Hanover, N.H. Special Rept. 43, Pt. II.

Bilello, M. A., and R. E. Bates. 1966, 1968, 1971, 1972, and 1975. Ice thickness observations, North American arctic and subarctic, 1970-71, 1971-72. U.S. Army Cold Regions Res. and Eng. Lab., Hanover, N.H. Rept. SR 43/3,4,5,6 and 7.

Black, R. F., and W. L. Barksdale. 1949. Oriented lakes of northern Alaska. J. Geol. 57:105-113.

Black, R. F. 1951. Eolian deposits of Alaska, p. 89-111. *In* Arctic V. 4(2).

Black, R. F. 1964. Gubik formation of quaternary age in northern Alaska. U.S. Geol. Surv. Prof. Pap. 302-C, p. 59-91.

Boland, D. H. P. 1976. Trophic classification of lakes using Landsat-1 (ERTS-1) multispectial scanner data. U.S. Environ. Protect. Agency, Assessment and Criteria Development Division, Corvalis Environ. Res. Lab., Corvalis, Oregon. 145 p.

Borror, D. J., D. M. Delong, and C. A. Triplehorn. 1976. An introduction to the study of insects. 4th ed. Holt Rinehart and Winston, N.Y.

Braden, S. 1979. Daily temperature maxima and minima at NPR-A oil exploration sites for 1978 and 1979. U.S. Geol. Survey, unpublished charts, ONPR-A, Anchorage, Alaska.

Brewer, M. C. 1958. The thermal regime of an arctic lake. Transactions, American Geophysical Union 39(2):278-284.

Britton, M. E. 1966. Vegetation of the arctic tundra. *In* H. P. Hansen [ed.], 2nd edition Arctic Biology. Oregon State Univ. Press. 64 p.

Brown, J., S. L. Dingman, and R. I. Lewellen. 1968. Hydrology of a drainage basin on the Alaskan Coastal Plain. U.S. Army Cold Regions Res. and Eng. Lab., Rept. RR 240, 18 p.

Bryan, M. L., and R. W. Larson. 1975. The study of freshwater lake ice using multiplexed imaging radar. J. Glac. 14(72):445-457.

Bunnel, F. L., S. F. Maclean, and J. Brown. 1975. Tundra Biome, Barrow, Alaska USA. *In* Rosswall, T., and O. W. Heal, [ed.] Structure and function of tundra ecosystems. Stockholm, Swedish Nat. Sci. Res. Council, Ecol. Bulletin 20.

Campbell, K. J., and A. S. Orange. 1974. Continuous sea and fresh water ice profiling using an impulse radar system, p. 432-443. *In* Advanced concepts and techniques in the study of snow and ice resources. Nat. Acad. of Sci., Washington, D.C.

Campbell, W. J., R. O. Ramseier, W. F. Weeks, and P. Gloersen. 1975. An integrated approach to the remote sensing of floating ice, p. 39-72. *In* Proceedings of the third Canadian Symposium on Remote Sensing 22-24 September 1975, Edmonton, Alberta.

Carson, C. E., and K. M. Hussey. 1960. Hydrodynamics of three arctic lakes. J. Geol. 68:585-600.

Carson, C. E., and K. M. Hussey. 1962. Oriented lakes of Arctic Alaska. J. Geol. 70(4):417-439.

Carter, L. D. and S. W. Robinson. 1978. Eolian sand and interbedded organic horizons at Kealok Creek on the Arctic Coastal Plain of Alaska: possible regional implications. U.S. Geol. Survey. Open File Rept. 78-320, 25 p.

Cowardine, L. M., V. Carter, F. Golet, and E. LaRoe. 1979. Classification of wetlands and deep water habitats of the United States. U.S. Gov. Print. Off., Washington, D.C. 103 p.

Davies, W. E. 1974. Geological and limnological factors of cold deserts. p. 53-61. *In* T. L. Smiley and J. H. Zumberge [ed.], Polar deserts symposium, Philadelphia, 1971. Univ. Arizona Press, Tucson.

Elachi, C., M. L. Bryan, and W. F. Weeks. 1976. Imaging radar observations of frozen arctic lakes. Remote Sensing of Environment 5:169-175.

Fenchel, T. 1975. The quantitative importance of the benthic microfauna of an arctic tundra pond. Hydrobiologia 48(4):445-464.

Frey, D. G., and J. B. Stahl. 1958. Measurements of primary production on Southhampton Island in the Canadian Arctic. Limnology and Oceanography 31:215-221.

Furniss, R. A., and D. L. Ward. 1975. Comparison of water availability for use in construction of proposed gas pipelines on the Alaskan North Slope. Alaska Biological Consultants. Anchorage, Ak. 69 p.

Greenwood, J. K., and R. S. Murphy. 1972. Factors affecting water management on the North Slope of Alaska. Inst. of Water Res. Rept. No. IWR 19, Sea Grant Rept. 72-3, 5 p.

Hall, D. K., and M. L. Bryan. 1977. Multispectral remote observations of hydrologic features on the North Slope of Alaska. Preprint. Greenbelt, Md., Goddard Space Flight Center. 38 p.

Hall, D. K. 1977. Determination of surface water volume and extent, water balance and interannual hydrolic variations on the Arctic Coastal Plain of Alaska. Nat. Aero. and Space Adm., Goddard Space Flight Center.

Head, P. C. 1971. An automated phenolhypochlorite method for the determination of ammonia in sea water. Deep-Sea Res. 18:531-532.

Hobbie, J. E. 1962. Limnological cycles and primary productivity of two lakes of the Alaskan Arctic. Unpub. Ph.D. dissert., Indiana Univ. 124 p.

Hobbie, J. E. et al. 1972. Carbon Flux through a tundra pond ecosystem at Barrow, Alaska. U.S. Tundra Biome Rept. 72-1, 29 p.

Hobbie, J. E. 1973. Arctic limnology: A Review. p. 127-168. *In* M. E. Britton [ed.], Alaska arctic tundra. Arctic Inst. of North America, Tech. Paper No. 25.

Hobbie, J. E. ed. 1980. Limnology of tundra ponds at Barrow, Alaska. Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania.

Hoffer, R. M. 1979. Computer-aided analysis of satellite and aircraft MSS Data for mapping snow-cover and water resources. LARS Tech. Rept. 020279, Purdue Univ., W. Lafayette, In. 16 p.

Hoge, F. E., R. N. Swift, and E. B. Frederick. 1980. Water depth measurement using an airborne pulsed neon laser system. Applied Optics 19(6):871-883.

Hoge, F. E. August 1980. Personal communication. Nat. Aero. and Space Adm., Wallops Flight Center, Wallops Island, Virginia.

Holmquist, C. 1973. Some arctic limnology and the hybernation of invertebrates and some fishes in sub-zero temperatures. Arch. Hydrobiol., Bd. 72, p. 49-69.

Holmquist, C. 1975. Lakes of northern Alaska and northwestern Canada and their invertebrate fauna. Zool. Jb. Syst., Bd. 102, p. 333-484.

Horowitz, A., and R. M. Atlas. 1977. Interactions of microorganisms and hydrocarbons following an accidental leakage of gasoline into a freshwater lake at Barrow, Alaska. Abstr., Annu. Meet Am. Soc. Microbiol.

Horowitz, A., A. Sexstone, and R. M. Atlas. 1978. Hydrocarbons and microbial activities in sediment of an Arctic lake one year after contamination with leaded gasoline. Arctic 31(3):180-191.

Howard, H. H., and G. W. Prescott. 1971. Primary production in Alaskan tundra lakes. The American Midland Naturalist 85 (1):108-123.

Hultén, E. 1974. Flora of Alaska and neighboring territories - a manual of the vascular plants. Stanford Univ. Press, Stanford, Ca. 1008 p.

Hutchinson, G. E. 1957. A treatise on limnology. v. 1. Wiley and Sons, New York.

Kalff, J. 1968. Some physical and chemical characteristics of arctic fresh waters in Alaska and northwestern Canada. J. Fish. Res. Bd. Canada 25:2575-2587.

Kalff, J. 1970. Arctic lake ecosystems. p. 651-663. *In* M. H. Holdgate [ed.], Antarctic Ecology. Academic Press.

Kalff, J. and H. E. Welch. 1974. Phytoplankton production in Char Lake, a natural polar lake, and in Meretta Lake, a polluted polar lake, Cornwallis Island, Northwest Territories. J. Fish. Res. Bd. Canada 31:621-636.

Kangas, D. A. 1972. Ecology of some arctic tundra ponds. Ph.D. thesis. Univ. Missouri. 343 p.

Keeney, D. R. 1973. The nitrogen cycle in sediment-water systems. J. Environ. Quality 2(1):15-29.

Kettle, D., and J. W. O'Brien. 1978. Vulnerability of arctic zooplankton species to predation by small lake trout. J. Fish. Res. Bd. Canada 36(11):1495-1500.

Kim, H. H., P. O. Cervenka, and C. B. Lankford. 1975. Development of an airborne laser bathymeter. Nat. Aero. and Space Adm. Technical Note, No. TN D-8079. Washington, D.C.

Kovacs, A. 1978. Remote detection of water under ice-covered lakes on the North Slope of Alaska. Arctic 31(4):448-458.

Kovacs, A., and R. M. Morey. 1979. Remote detection of a freshwater pool off the Sagavanirktok River Delta, Alaska. Arctic 32(2): 161-164.

Likens, G. E., and P. L. Johnson. 1968. Limnological reconnaissance in interior Alaska. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N.H. Rept. RR 239, 41 p.

Lind, Owin T. 1979. Handbook of common methods in limnology. 2nd ed., C.V. Mosby Co. St. Louis, Missouri. 199 p.

Livingstone, D. A. 1963. Alaska, Yukon, Northwest Territories, and Greenland. p. 559-574. *In* D. G. Frey [ed.], Limnology in North America. Univ. Wisconsin Press.

Lyzenga, D. R. 1978. Passive remote sensing techniques for mapping water depth and bottom features. Applied Optics 17(3):379-383.

Mackay, J. R. 1956. Notes on oriented lakes of the Liverpool Bay Area, Northwest Territories. p. 169-173. *In* Rivers Canadiene de Geographic, v. 10.

Mausel, P. W. et al. 1974. Evaluation of surface water resources from machine - processing of ERTS multispectral data. J. Environ. Quality 3(4):316-321.

McFadden, J. D. 1965. The interrelationship of lake ice and climate in central Canada. PhD. thesis. Univ. Wisconsin. 120 p.

McFadden, T. and C. Collins. 1978. Fresh water supply for a village surrounded by salt water--Point Hope, Alaska. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N.H. 18 p.

Mellor, J. C. 1978. Resources associated with wetlands and lake basin depth in NPR-A: a bibliographic essay. Unpublished BLM Rept.

Mellor, J. C., P. Reynolds, and W. Clithero. 1978. Summer 1978 assessment of proposed NPR-A well sites. Bureau of Land Mgt./Nat. Petroleum Reserve-Alaska Special Environ. Rept., Fairbanks, Ak. 70 p.

Mellor, J. C. 1980. Side-Looking Airborne Radar application for recording and monitoring winter roads and trails. p. 78-93. *In* Workshop on Winter Roads 18-19 October 1979 Ottawa, Ontario. Nat. Res. Council Canada Tech. Memo. No. 129.

Merritt, R. W., and K. W. Cummins. [eds.] 1978. An introduction to the aquatic insects of North America. Kendall Hunt Pub. Co., Dubuque, Iowa.

Mozley, S. C. 1979. Comparative survey of benthic macroinvertebrates in thirteen arctic Alaskan lakes. Poster Session, North American Benthological Soc., Erie, PA.

Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27:31-36.

NANA Environmental System Incorporated. 1976a. Water supply source report Prudhoe Bay, Alaska, March 1976. Arctic Environ. Eng., Anchorage, Ak. 9 p.

NANA Environmental System Incorporated. 1976b. Water resources proposal for Prudhoe Bay, Alaska, May 24, 1976. Arctic Environ. Eng., Anchorage, Ak. 50 p.

Netsch, N., E. Crateau, G. Love, and N. Swanton. 1977. Preliminary Report -- freshwater fisheries reconnaissance of the coastal plain of National Petroleum Reserve-Alaska (NPR-A), U.S. Fish and Wildlife Service, Anchorage, Ak. 34 p.

Nyquist, D., J. D. La Perriere. 1973. A preliminary survey of the zooplankton and benthos of an arctic lake near Prudhoe Bay, Alaska. Entomol. News 84(7):227-234.

O'Brien, J. W., and D. G. Huggins. 1974. The limnology of the Noatak drainage. p. 159-223. *In* S. B. Young [ed.], The environment of the Noatak River Basin, Alaska. Contributions from the Center for Northern Studies No. 1.

O'Brien, J. W. and D. Kettle. 1978. Helmets and invisible armor: structures reducing predation from tactile and visual planktivores. Unpublished Rept., Dept. of Systematics and Ecology, Univ. Kansas, Lawrence, Kansas.

Olhoeft, G. R. 1977. Electrical properties of natural clay permafrost. Canadian J. of Earth Sciences 14(1):16-24.

Outcalt, E. E. 1979. Radar ice thickness surveys. Innovative Ventures Ltd., Calgary, Alberta.

Page, D. F., and R. O. Ramseier. 1975. Application of radar techniques to ice and snow studies. J. Glac. 15(73):171-91.

Pearse, G. A. 1977. Inventory and cataloging of arctic area waters. Alaska Dept. of Fish and Game, Sport Fish Div., Study G-I-I. 18:93.

Pennak, R. W. 1978. Freshwater invertebrates of the United States, 2nd ed. John Wiley and Sons, N.Y.

Pounder, E. R. 1965. The physics of ice. Pergamon Press, N.Y. 151 p.

Power, G. 1978. Fish population structure in arctic lakes. J. Fish. Res. Bd. Canada 35(1):53-59.

Prentki, R. T. 1976. Phosphorus cycling in tundra ponds. Ph.D. dissert., Univ. Alaska, Fairbanks, Ak.

Reed, E. B. 1962. Freshwater plankton crustacea of the Colville River area, northern Alaska. Dissertation exerpt. Univ. Saskatchewan.

Reynolds, P., J. C. Mellor, and W. Clithero. 1979. Summer 1979 assessment of proposed NPR-A well sites. Bureau of Land Mgt./Nat. Petroleum Reserve-Alaska Special Environ. Rept., Fairbanks, Ak. 50 p.

Rex, R. W. 1961. Hydrodynamic analysis of circulation and orientation of lakes in northern Alaska. p. 1021-1043. *In* G. O. Roasch [ed.], Geol. of the Arctic, Univ. Toronto Press.

Salomonson, V. V., and A. Rango. 1973. Water resources. p. 115-126. *In* Symposium on sig. res. obtained from ERTS-1. Goddard Space Flight Center. Greenbelt, Maryland.

Sater, J. E. 1961. The Arctic Basin. Arctic Inst. of North America. 337 p.

Schindler, D. W. 1978. Factors regulating phytoplankton production and standing crop in the world's freshwaters. Limnology and Oceanography 23(3):478-486.

Sellmann, P. V., K. L. Carey, C. M. Keeler, and A. D. Hartwell. 1972. Terrain and coastal conditions on the Arctic Coastal Plain. Arctic environ. data package. Supplement 1. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N.H. Rept. SR 165/1, 83 p.

Sellmann, P. V., W. F. Weeks, and W. J. Cambell. 1975a. Use of Side-Looking Airborne Radar to determine depth on the Alaskan North Slope. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N.H. Special Rept. No. 230.

Sellmann, P. V., J. Brown, R. I. Lewellen, H. McKim, and C. Merry. 1975b. The classification and geomorphic implication of thaw lakes on the Arctic Coastal Plain, Alaska. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N.H. Res. Rept. No. 344, 40 p.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming. 1942. The oceans. Prentice-Hall, Inc., Englewood Cliffs, N.J. 105 p.

Skreslet, S., and N. Foged. 1970. The ecosystem of the arctic Lake Nordlaguna Jan-Mayen Island, part 2, plankton and benthos. Astarte 3(2):53-61.

Sloan, C. E. 1977. NPR-A 105(c) assessment surveys. Unpublished U.S. Geol. Survey Rept. Anchorage, Alaska.

Spetzman, L. A. 1959. Vegetation of the arctic slope of Alaska. U.S. Geol. Surv. Prof. Pap. 302-B, p. 19-58.

Stanley, D. W. 1972. Benthic algae productivity in tundra ponds and lakes. IBP Tundra Biome Project 3936, N. Carolina State Univ. Raleigh, N.C. 8 p.

Stanley, D. W. 1974. Production ecology of epipelic algae in Alaskan tundra ponds. Ph.D. Thesis, N. Carolina State Univ., Raleigh, N.C. 155 p.

Stanley, D. W. 1976a. Productivity of epipelic algae in tundra ponds and a lake near Barrow, Alaska. Ecology 57(5):1015-1024.

Stanley, D. W., and R. J. Daley. 1976b. Environmental control of primary productivity in Alaskan tundra ponds. Ecology 57(5):1025-1033.

Stanley, D. W. 1976c. A carbon flow model of epipelic algal productivity in Alaskan tundra ponds. Ecology 57(5):1034-1042.

Strickland, J. D. H. and T. R. Parsons. 1968. A practical handbook of seawater analysis. Bulletin 167, Fisheries Res. Board of Canada, Ottawa. 311 p.

Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1. 1973. S. C. Freden et al. [eds.], Nat. Ocean and Atmos. Adm., Washington, D.C.

Talling, J. F. 1971. The underwater light climate as a controlling factor in the production ecology of freshwater phytoplankton. Mitt. Internat. Verein. Limnol. Stuttgart 19:214-243.

Tarnocai, C., and S. J. Kristof. 1975. Computer-aided classification of land and water bodies using ERTS Data - Mackenzie Delta area, N.W.T. LARS Info. Note 031875, Purdue Univ. W. Lafayette, Ind., p. 14.

Thormodsgard, J. 1980. Personal Communication. EROS Data Center Sioux Fall, S.D.

U.S. Dept. of Army. 1978. Operator's manual, OV-ID/RV-1D aircraft, T.M. 55-1510-213-10, Headquarters Dept. of Army, Washington, D.C.

U.S. Dept. of Army. 1979. Operator and maintenance manual, radar surveillance set AN/APS-94E. T.M. 11-5895-967-12, Headquarters Dept. of Army, Washington, D.C.

U.S. Dept. of the Int. 1977. Study Report 2, values and resource analysis, v. 3. National Petroleum Reserve-Alaska Task Force, 105(c) land use study, Anchorage, Alaska.

U.S. Dept. of the Int. 1978. Ecological Profile, National Petroleum Reserve-Alaska, 105(c) land use plan. U.S. Dept. of the Int. Interagency Planning Team. 103 p.

U.S. Geological Survey. 1979. Landsat data users handbook. U.S. Geol. Surv., Arlington, Virginia.

Vant, M. R., R. B. Gray, R. O. Ramseier, and V. Makios. 1974. Dielectric properties of fresh and sea ice at 10 and 35 GHz. J. Appl. Phys. 45(11):4712-4717.

Vickers, R. S., J. E. Heighway, and R. T. Gedney. 1974. Airborne profiling of the ice thickness using a short pulse radar. p. 422-431. *In* Advanced concepts and techniques in the study of snow and ice resources. National Academy of Science, Washington, D.C.

Vollenweider, R. A. 1968. A manual on methods for measuring primary production in aquatic environments, IBP Handbook No. 12. Blackwell Scientific Publ., Oxford. 113 p.

Walker, H. J. 1967. River sand dunes in the Colville Delta, Alaska: Louisiana State Univ. Coastal Studies Bull. 1, p. 7-14.

Walker, H. J. 1973. Morphology of the North Slope. pp. 49-52. *In* M. E. Britton [ed.], Alaskan Arctic Tundra. Arctic Inst. North America Tech. Pap. 25.

Weaver, D. F. 1966. Radiation regime over Arctic tundra and lake. Washington University, Dept. of Atmos. Sci., Sci. Rept., May 1970-No. 6, 31 p.

Weeks, W. F., P. Sellmann, and W. J. Campbell. 1977. Interesting features of radar imagery of ice-covered North Slope lakes. J. Glaciology 78:129-135.

Weeks, W. F., A. G. Fountain, M. L. Bryan, and C. Elachi. 1978. Differences in radar return from ice covered lakes. J. of Geophysical Res. 83(C8):4069-4073.

Wiesnet, D. R. 1974. The role of satellites in snow and ice measurements. p. 447-456. *In* Advanced concepts and techniques in the study of snow and ice resources. Nat. Acad. of Sci. Washington, D.C.

Wiggins, G. B. 1977. Larvae of the North American caddisfly genera (Trichoptera). Univ. Toronto Press, Buffalo, N.Y.

Williams, J. R., W. E. Yeend, L. D. Carter, and T. D. Hamilton. 1977. Preliminary surficial deposits map of National Petroleum Reserve-Alaska. U.S. Geol. Sur. open-file Rept. 77-868, 2 sheets.

Wilson, W. J., E. H. Buck, G. F. Player, and L. D. Dreyer. 1977. Winter water availability and use conflicts as related to fish and wildlife in Arctic Alaska - a synthesis of information. Arctic Environmental Information and Data Center, Univ. Alaska, Anchorage. 222 p.

Wong, J., J. R. Rossiter, G. R. Olhoeft, and D. W. Strangway. 1977. Permafrost: electrical properties of the active layer measured *in situ*. Canadian J. Earth Sci. 14(4:1):582-586.

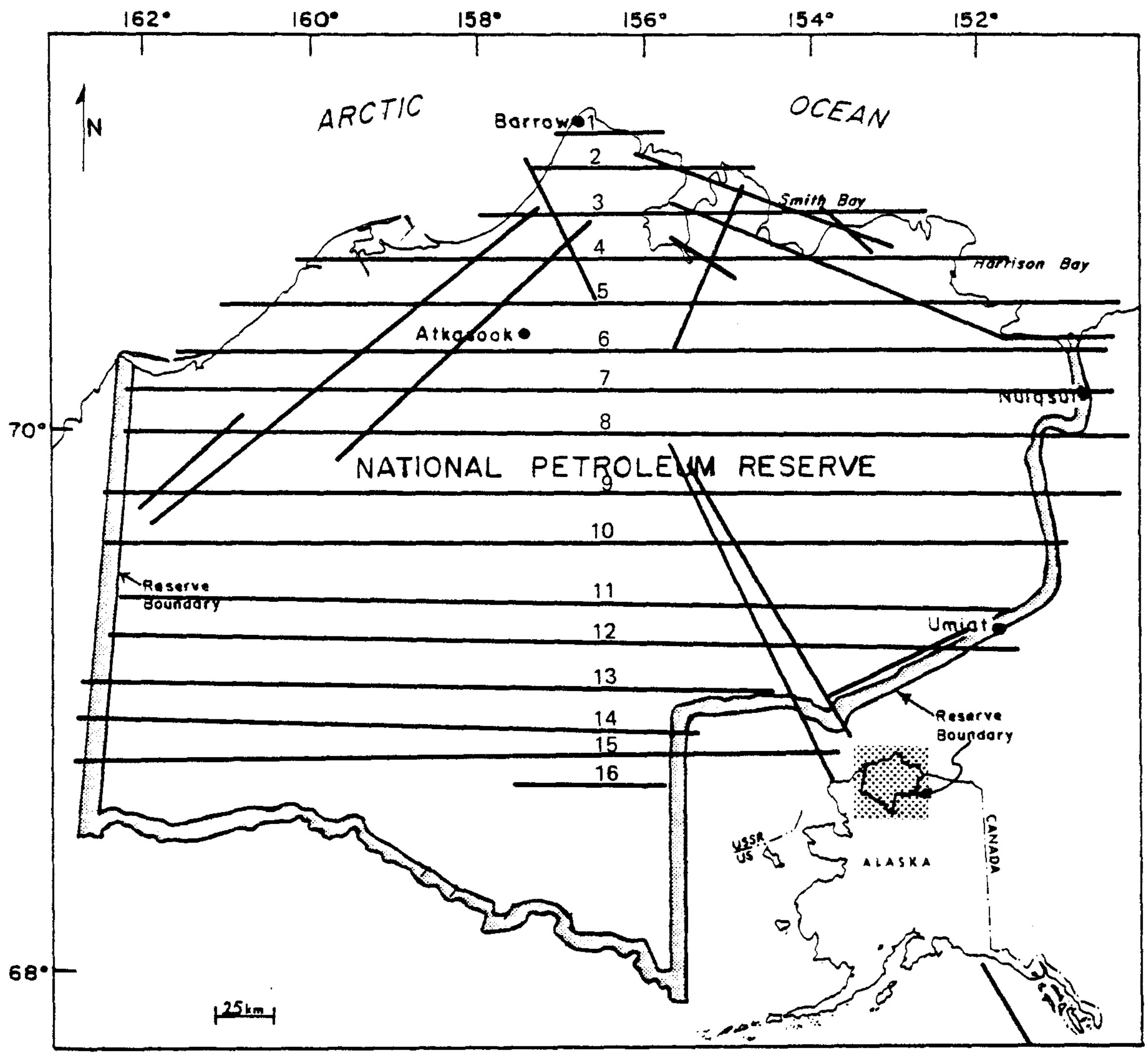
Work, E. A., D. S. Gilmer, and A. T. Klett. 1973. Preliminary evaluation of ERTS-1 for determining numbers and distribution of prairie ponds and lakes. p. 801-808. *In* Symposium on significant results obtained from the ERTS-1. Nat. Aero. and Space Adm., SP-327, Washington, D.C.

Work, E. A., and D. S. Gilmer. 1976. Utilization of satellite data for inventorying prairie ponds and lakes. Photogrammetric Engineering and Remote Sensing 42(5):684-694.

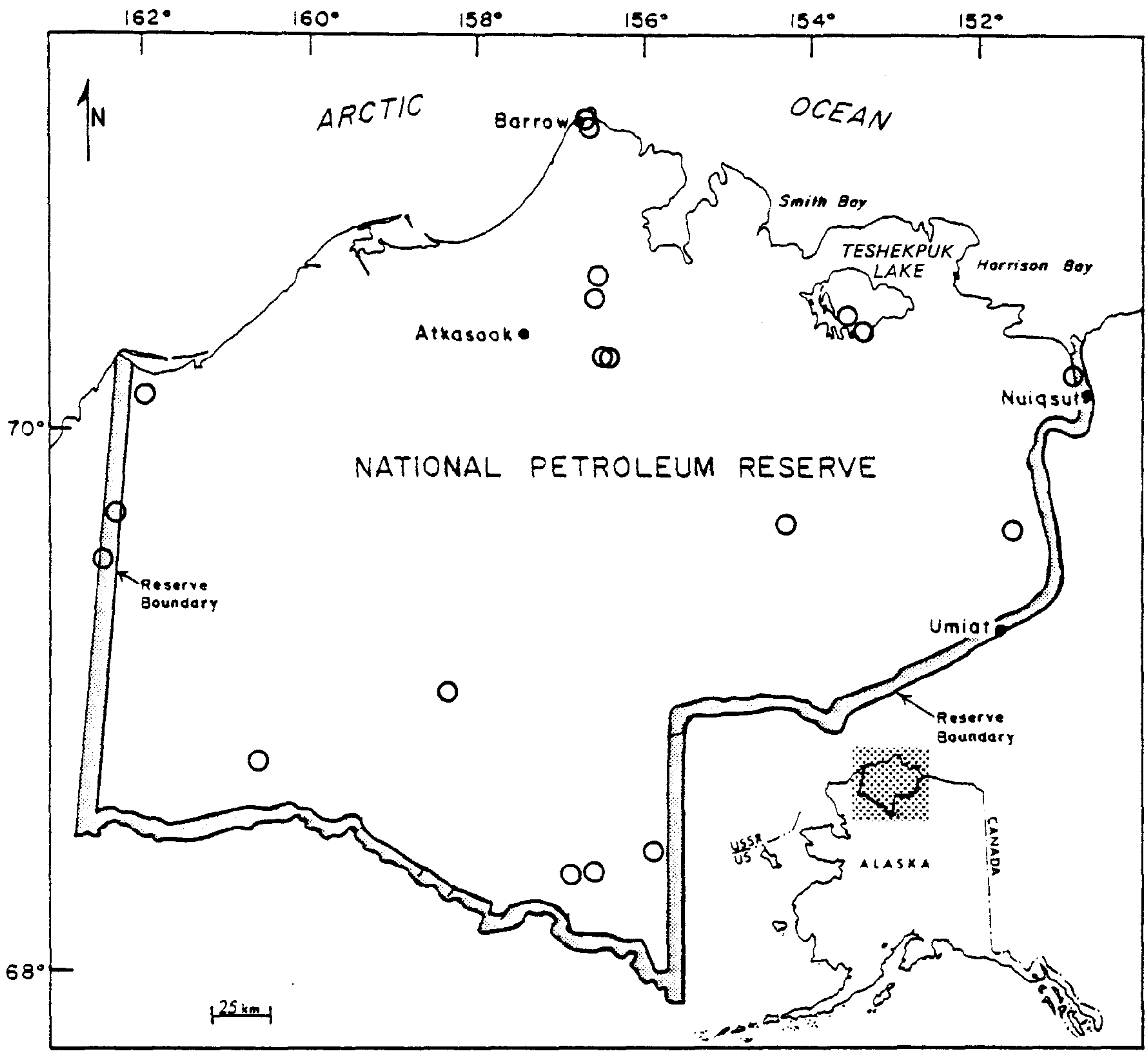
Zhadin, V. I., and S. V. Gerd. 1961. Fauna and flora of the rivers, lakes and reservoirs of the U.S.S.R. Oldbourne Press, London. p. 304-311.

APPENDIX A

APRIL 1980 LAKE AND SLAR DATA SUMMARY FOR THE NATIONAL PETROLEUM RESERVE IN ALASKA



Appendix Fig. A-1. SLAR image flight lines, 7-11 April 1980.



Appendix Fig. A-2. Lakes sampled 6-15 April 1980. Latitude and longitude positions and data collected are in Table A-1.

Appendix Table A-1. Lake data sampled 6-15 Apr. 80.

Lake Identification	Date Sampled April '80	Latitude	Longitude	Dissolved Oxygen (ml/ℓ) *I/W	Dissolved Oxygen (ml/ℓ) **W/S	Temperature (°C) *I/W	Temperature (°C) **W/S	Specific Conductance (μmhos)	Chlorophyll *a* in water column (mg/m^3)	NUTRIENTS ($\mu gat/\ell$ = $\mu mole/\ell$) NH_3	$NO_2 + NO_3$	NO_2	PO_4	SUMMARIZED SNOW, ICE AND WATER DEPTH MEASUREMENTS Snow Thickness (cm) Av.	Snow Thickness (cm) Rg.	Av. Free-Board (cm)	Av. Overice (cm)	Max. Water Depth (m)	Ice Thickness (cm) Av.	Ice Thickness (cm) Rg.	No. of Holes	% Snow Cover
1. (A-1) Imikpuk	15	71°20.2'	156°39.1'	2.1	1.8	0.1	0.1	2310	2.1 & 17.9	33.1 & 28.7	3.2 & 4.8	0.42 & 0.37	0.35 & 0.15	10	0-21	10	20	2.8	190	167-210	5	98
2. (A-2) Ikroavik	7	71°13.9'	156°37.9'	-	-	-	-	624	0.2	16.8	8.1	2.48	0.20	29	26-33	4	0	2.3	146	142-153	4	100
3. (B-1)	8	70°22.9'	156°23.4'	3.3	1.9	0.5	2.0	328	1.2	1.1	14.0	0.27	2.65	15	14-16	6	0	6.2	156	153-160	4	99
4. (B-2)	8	70°23.2'	156°28.0'	0.9	0.8	0.5	0.5	320	3.2	25.0	0.3	0.46	0.85	27	22-32	4	0	2.0	144	143-145	2	100
5. (C-1) Betty	8	68°28.6'	156°29.5'	8.5	1.5	0	2.7	70	2.8	1.4	10.2	0.35	1.15	10	9-12	11	12	5.6	170	156-179	4	100
6. (C-2)	14	68°27.9'	156°44.5'	4.5	4.5	0.6	0.6	72	1.4	3.9	29.3	1.29	3.20	30	26-36	2	13	1.8	132	131-133	4	100
7. Awuna	6	69°08.5'	158°08.5'	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2.2	130	-	1	-
8. (SLAR 1)	12	70°42.5'	156°31'	5.2	5.2	0.4	0.4	580	1.6	17.4	7.5	0.35	0.10	19	14-25	8	2	2.0	156	150-161	3	100
9. (SLAR 3)	12	70°37'	156°34'	1.0	1.0	0.1	0.1	1078	4.6	126.8	0.4	0.94	0.35	32	-	0	0	1.6	142	-	1	100
10. Ivotuk	14	68°33'	156°01.5'	8.1	2.5	0.8	3.0	57	-	-	-	-	-	3	-	8	0	10.0	138	135-140	2	-
11. Sikolik	9	70°10'	161°29'	8.1	8.1	0.3	0.3	457	3.2	0.8	12.9	0.25	0.30	20	17-22	5	5	2.0	164	156-172	2	95
12. #92	10	69°43'	161"49.5'	5.6	5.6	0.7	0.7	330	0.7	0.7	2.1	0.29	0.45	28	20-40	3	0	2.0	130	117-137	3	99
13. #92 South	10	69°32'	161°54'	0.9	0.8	0.8	0.5	475	1.9	4.6	3.8	0.37	1.40	17	8-36	10	0	2.0	148	136-155	3	99
14. No Luck	10	68°47.5'	160°00'	0.8	0.6	0.5	0.5	326	1.2	2.4	19.3	0.52	3.40	8	0-15	12	12	2.5	159	140-169	4	90
15. Teshekpuk 1	13	70°33'	153°43'	12.3	10.5	0.1	1.6	357	1.6	0.4	2.4	0.06	0.35	20	17-24	10	12	5.6	178	172-183	2	75
16. Teshekpuk 2	13	70°29'	153°30'	12.4	8.8	0.2	1.7	447	1.2	0.5	3.2	0.19	0.65	21	18-24	4	0	4.0	156	150-162	3	-
17. Oil Lake South	13	70°16.5'	151°08.5'	0.9	0.7	0.2	0.3	1150	1.2	32.5	2.6	0.37	0.50	19	14-25	7	3	2.1	154	145-162	3	100
18. #284	13	69°42.2'	151°58.5'	0.9	0.5	0.5	2.2	487	-	-	-	-	-	26	22-30	5	5	3.4	141	122-154	3	100
19. Kokuktak	14	69°46'	154°26'	2.4	0.8	0.2	2.4	522	1.6	2.5	8.0	0.89	2.90	15	12-17	12	5	3.4	167	162-173	3	100
				4.6 Av.	3.3 Av.	0.4 Av.	1.2 Av.	555 Av.	2.8 Av.	17.6 Av.	7.8 Av.	0.58 Av.	1.11 Av.	19 Av.	0-40 Rg.	8 Av.	5 Av.	3.3 Av.	153 Av.	117-210 Av.	56 Total	97 Av.

* I/W = Ice/water interface
**W/S = Water/substrate interface

APPENDIX B

SATELLITE LAKE SYSTEM MANUAL

CONTENTS

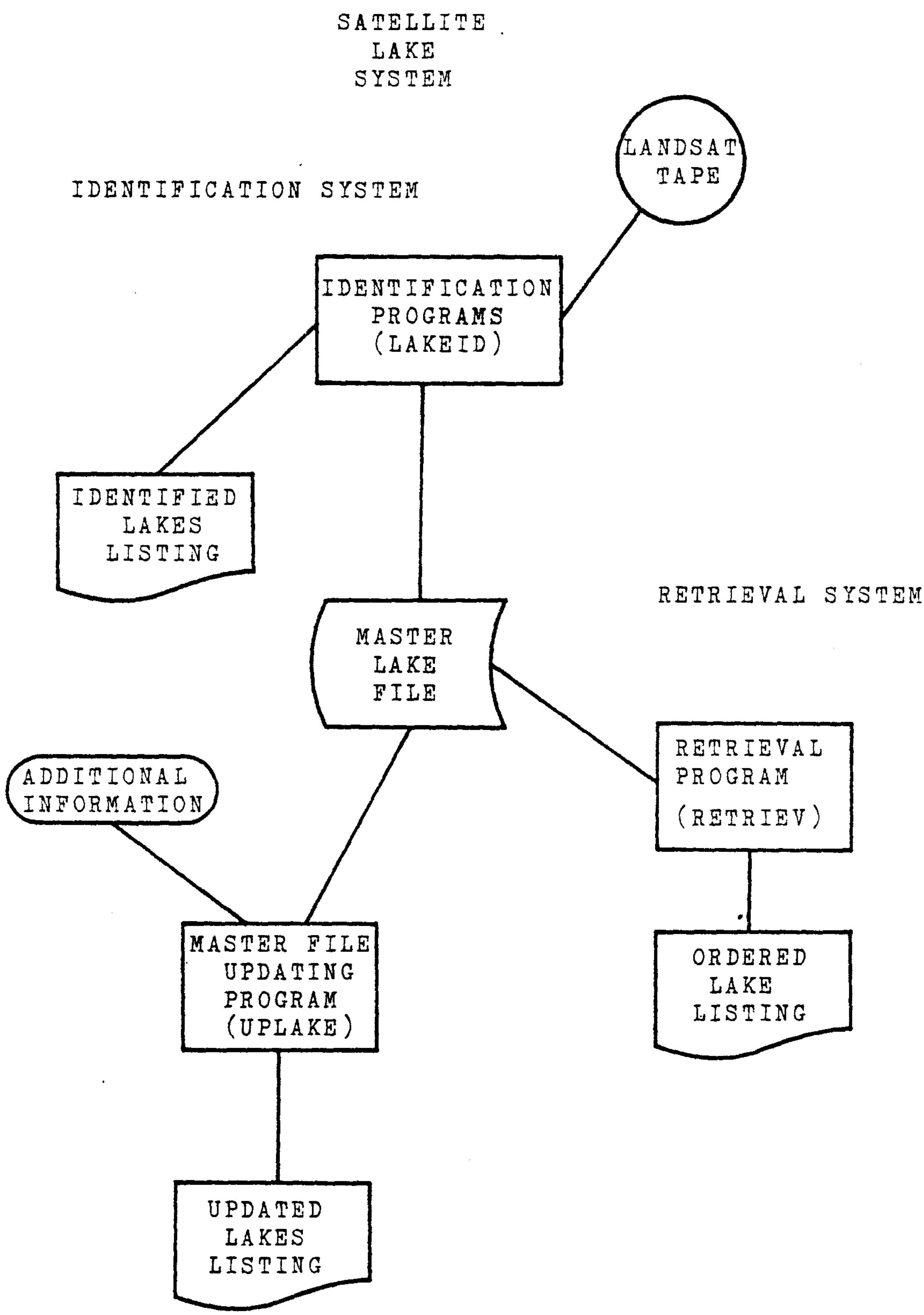
SATELLITE
LAKE
SYSTEM

A system of programs and procedures was established to acquire as much information pertaining to lakes as possible to date, and to store this information in a way such that retrieval would be rapid, orderly, and inexpensive.

The data base chosen for creating the initial lake file was Landsat Satellite Computer Compatible Tapes (CCT). A description of and information necessary to the processing of these tapes is given in the Tape Handling and Procedures section of the User Guide.

The Satellite Lake System is actually comprised of two completely separate systems of programs written to be executed on the Honeywell Information System (HIS) 66/20 with Dual Processors. These systems may be combined and run as one or can stand alone. They are henceforth referred to as the Identification and Retrieval Systems.

The driver programs are written in FORTRAN and run under Time Sharing Session (TSS). The main system programs and associated subroutines are run in batch and require Job Control Language (JCL) files since they either use magnetic tapes or are written in COBOL which requires a batch run.


SATELLITE
LAKE
SYSTEM
IDENTIFICATION SYSTEM
LANDSAT TAPE
IDENTIFICATION PROGRAMS (LAKEID)
IDENTIFIED LAKES LISTING
RETRIEVAL SYSTEM
MASTER LAKE FILE
ADDITIONAL INFORMATION
RETRIEVAL PROGRAM (RETRIEV)
MASTER FILE UPDATING PROGRAM (UPLAKE)
ORDERED LAKE LISTING
UPDATED LAKES LISTING

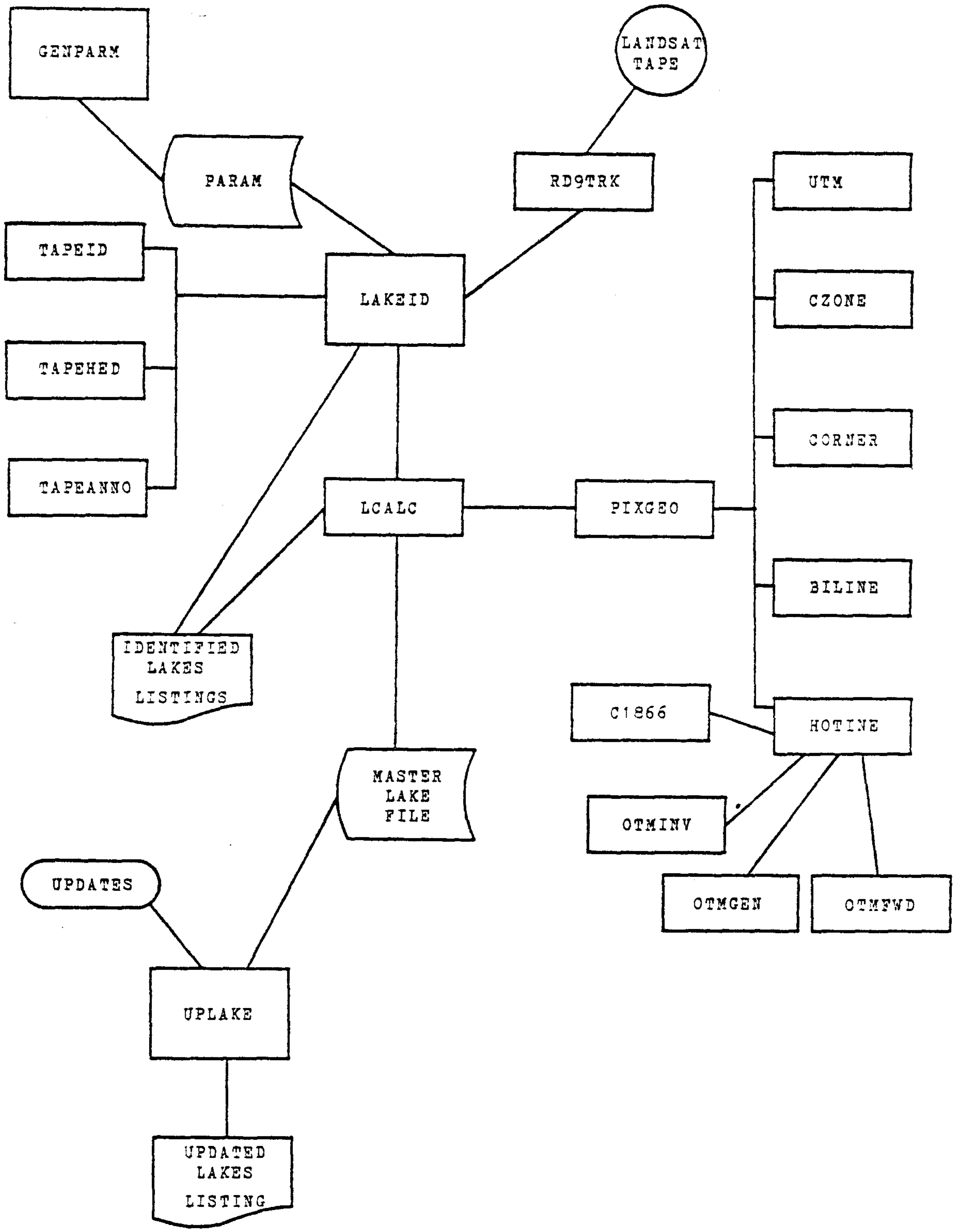
IDENTIFICATION
SYSTEM
OVERVIEW

A driver program, written in FORTRAN, was developed to read and process Landsat CCT's. With the help of several subroutines, pixel values stored on the tapes are interpreted as either land or water, and lake boundaries are consequently established. Various calculations are performed for each lake, and the lake is uniquely defined by the latitude and longitude of its centroid. All complete lakes are listed and written to a file along with all relevant information.

Additional information may be added to each individual lake record by the updating COBOL program UPLAKE. The output consists of a listing of all updated lakes on file and a complete master lake file. This master lake file may then be used as input to the Retrieval System of programs.

A complete description follows for each main program and all called subroutines. File descriptions and instructions for job submission to the computer are included.

IDENTIFICATION SYSTEM



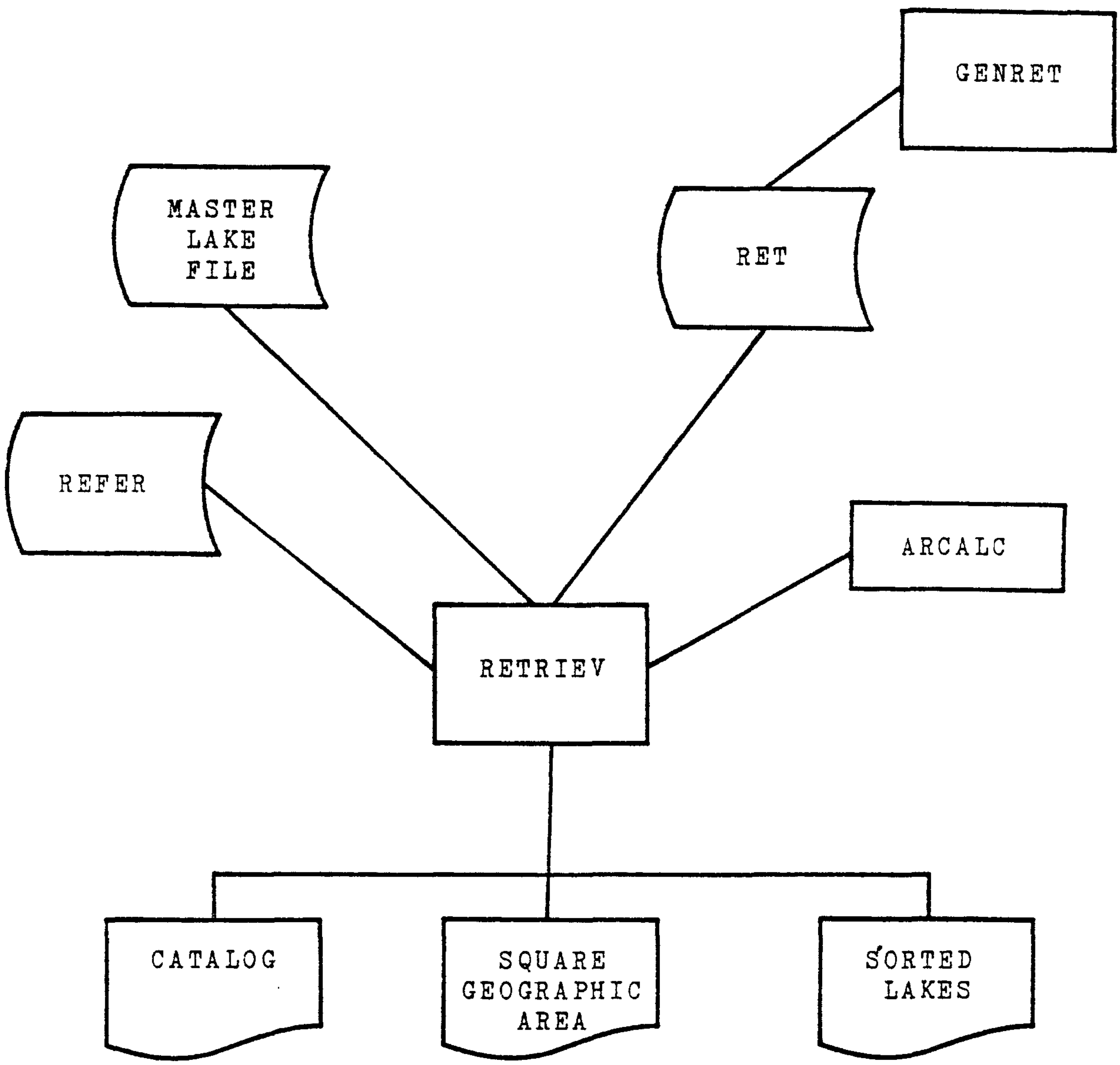
RETRIEVAL SYSTEM OVERVIEW

The objectives of the Identification System are to identify lakes from a Landsat CCT data base by unique centroid given in latitude and longitude coordinates, to calculate various parameters for each lake, to list the lakes, and inevitably, to append a master lake file with information pertaining to the individual lakes found. This master lake file is then used as a data base for the Retrieval System.

The Retrieval System is required to list the file in three general ways: as a catalog, by sorting on a particular field, or by enumerating those within a specified geographic area, and by filtering on one or more fields.

A complete description follows for each program and called subroutine. File descriptions and instructions for job submission to the computer are included.

RETRIEVAL SYSTEM



USER GUIDE

INTRODUCTION

The Satellite Lake System manual provides complete documentation for all programs and procedures including tape handling and job submission to the computer for the entire system. Although the documentation provided for programs and subroutines is programmer oriented it is advisable for any user to read all information provided for his particular task.

The following pages contain a step-by-step "HOW TO" approach to the mechanics involved in the actual running of the various program tasks.

WHAT IS AVAILABLE

TO ADD ADDITIONAL LAKES TO THE MASTER FILE

This is accomplished through the Identification System and should be done under the supervision of someone who has successfully completed it in the past if possible.

PROCEDURES

1. Obtain the correct EDIPS Landsat CCT-PM for the area of interest and take it to the main computer center at Bunnell Building.
2. Read Tape Handling and Procedures carefully and follow all directions.
3. Read documentation for Identification System.
4. Read documentation for programs GENPARM and LAKEID.
5. Follow RUN instructions provided for program GENPARM and LAKEID.
6. Merge lake files into Master Lake File (additional program needs to be developed in the future).

TO APPEND ADDITIONAL INFORMATION TO LAKES

Once the lake is added to the master file with all the calculated information included, additional information for any lake may be added to the record on the file by the program UPLAKE which is part of the Identification System.

PROCEDURE

1. Read all documentation for Identification System.
2. Since the lake may only be accessed through its 17-digit latitude and longitude key it is imperative that the user have the exact key.
   These keys are available from previous runs of the update program or from the listing provided by the LAKEID program which was used to create the lake file initially.
3. Read documentation for UPLAKE.
4. Follow the RUN directions provided in the documentation for the program UPLAKE which is the updating program for the Master Lake File.
5. When updating is complete the output should be checked to insure that all additional information is appended to the lake records intended. If an error is detected the update records should be corrected and the program may be re-run.

TO LIST (RETRIEVE) THE MASTER LAKE FILE

The lakes on the master file may be retrieved or listed through the Retrieval System. The types of lists available are fully described in the documentation for the Retrieval System and all associated programs and subroutines.

PROCEDURES

1. Read all directions provided in the documentation for the Retrieval System.
2. Determine if the listing desired is possible to obtain and if so proceed to run.

PROBLEMS

Since the average user is often not familiar with the computer some problems can arise which can easily be solved. Some of these are listed here in order of procedure .

1. NO POWER

   Check plug or ask for help

2. NO RESPONSE TO "CTRL" & "A" COMMAND

   Make sure terminal is connected to HIS

   If connected ask for help

3. CAN'T SEE RESPONSES YOU TYPE

   This indicates that the terminal is in full duplex mode (FDX). Push FDX key down for half-duplex (HDX) which is required by Honeywell. It is important to remember that although you can't see what you just typed the computer has received every key stroke.

4. TYPING ERRORS

   To eliminate an entire line simultaneously push the "CTRL" & "8" keys. The "@" will erase one letter at a time (e.g. if you typed the last two letters wrong immediately follow them with two "@"'s to erase them from the computer's input).

5. ILLEGAL COMMAND

This message indicates that the command was either typed wrong or there is no such command. Check spelling of command and try again.

6. SYSTEM CRASH

This may or may not be a problem. Ask for help.

GENERAL TIME SHARING INSTRUCTIONS

The following is a list of instructions for the beginning computer user. They will enable the user of the Satellite Lake System to get onto the computer and arrive at what is regarded as "SYSTEM" level. From that point on he should consult the documentation directly for further instructions or he may sign off by typing "BYE" and end his session at that point.

1. Turn power switch to enable terminal.
2. Simultaneously push "CTRL" and "A" keys.
3. After the "USERID?" prompt respond with your USERID and push the carriage return [CR].
4. The next prompt will overwrite. You should type your password and push [CR]. Your password will be overwritten for security.
5. The system will prompt you with a "*". You are now at what is considered to be "SYSTEM" level. You may either proceed with your session or terminate the session by typing "BYE". Simply powering off will leave your files accessable for 10 minutes.

TAPE HANDLING AND PROCEDURES

DESCRIPTION

Landsat CCT data, received by National Aeronautics and Space Administration (NASA) tracking stations and converted into digital form, are stored on magnetic tape and used as a data base for this system of programs.

EDIPS CCT-PM tape type is used. Extensive documentation regarding this type may be obtained in the Manual on Characteristics of Landsat Computer-Compatible Tapes Produced by the EROS Data Center Digital Image Processing System. The manual is available from the Landsat Library in the Elvey Building on the University of Alaska compus at Fairbanks, Alaska.

PHYSICAL CHARACTERISTICS OF CCT FOR USE WITH THIS SYSTEM

1. BIL - band interleaved by line
2. 1600 BPI density and 9-track
3. IBM produced binary and ASCII headers, binary data, 8-bit bytes at 4 bytes per word, 1 pixel per byte
4. Normal scene processed will be contained on 2 tape volumes with 5964 data records on the first volume and 5968 on the second. The format follows.

TAPE 1

DIRECTORY (1 RECORD 90 WORDS)

EOF (End of File Mark)

HEADER (2 RECORDS 899 WORDS EACH)

EOF (End of File Mark)

DATA (5964 RECORDS 899 WORDS EACH)

EOF (End of File Mark)

TRAILERS

EOV (End of Volume Mark)

TAPE 2

DIRECTORY (1 RECORD 90 WORDS)

EOF (End of File Mark)

DATA

EOF (End of File Mark)

TRAILERS

EOS (End of Scene Mark)

DATA STRUCTURE

RECORD 1...BAND 4...IMAGE LINE 1

RECORD 2...BAND 5...IMAGE LINE 1

RECORD 3...BAND 6...IMAGE LINE 1

RECORD 4...BAND 7...IMAGE LINE 1

RECORD 5...BAND 4...IMAGE LINE 2

RECORD 6...BAND 5...IMAGE LINE 2

RECORD 7...BAND 6...IMAGE LINE 2

. . .

. . .

. . .

. . .

HEADER RECORDS

The directory, header, and annotation records are described in detail in the Landsat CCT manual. Bytes within words may be stored in either binary or ASCII. An example of a dump of one Landsat tape is included in this documentation.

The header record is used for data descriptions. A full byte-by-byte description is included in the Landsat CCT manual (USGS 1979). It also describes the annotation record which follows the header record on the tape. The annotation record contains all of the information printed on the bottom of the associated film product (image) and information concerning the location and coordinates of the tick marks which surround the corrected image. Each tick mark is 9 bytes and its distance from the image data area represents a ground distance of 1000 meters.

The tick marks are used by the subroutines in the conversion of the centroid coordinates to latitude and longitude. This process is described in detail in the program documentation for LCALC.

Byte 84 of the annotation record gives the type of projection used in that particular tape. The Hotine Oblique Mercator (HOM) projection was used for this system.

The correction applied to the data is also carried on the annotation record in byte 82. Geometric registration error assessment must be made according to the level of correction and from the number of ground control points (GCP) used. Quality assessment of applied geometric modeling is available in byte 232 of the header record. Assessment codes range from 0 to 9. The minimum number of GCP's used in a scene may be calculated by setting the assessment code equal to the truncated integer value of the expression (N+7)/8 where N is the number of ground control points. A "1" or "0" code may have a maximum of up to 44 pixels or 2.5 km geometric error. Geometric correction through use of ground control points may limit errors to 1 pixel or 57 m at higher codes (5-9). Goddard Space Flight Center has not released any accuracy assessment key to the codes which must be used as qualitative rather than quantitative geometric accuracy assessment indicators.

IMAGE DATA STORAGE

The data is stored in binary. The first 12 bytes of each record are used as annotation for that record, the next 3548 bytes are image pixel values, and the last 48 bytes are calibration and zero fill.

TAPE STORAGE AND HANDLING

All Landsat CCT'S are stored in the Geophysical Institute Landsat Library located in the Elvey Building at the University of Alaska in Fairbanks. Specific tapes may be ordered through the librarian. After having obtained the tapes required, they must be labeled and numbered for computer access. Information for tape handling is available from anyone in Data Processing. Landsat CCT configuration is as follows:

1 WORD = 4 BYTES

1 BYTE = 3 OCTAL DIGITS IN DUMP = 8 BITS

EX. WORD 014016010007 =

BYTES 014 016 010 AND 007 (IN OCTAL)

OCTAL 014 = DECIMAL 12

OCTAL 016 = DECIMAL 14

OCTAL 010 = DECIMAL 8

OCTAL 007 = DECIMAL 7

SATELLITE LAKE SYSTEM PROGRAMMER GUIDE

The Satellite Lake System Manual was written for both the programmer and the user in general. The documentation for the individual programs and subroutines is programmer oriented and contains specific details about the programs which are essential to both running and modification. All tape handling and tape format descriptions are included in the User Guide and should be examined thoroughly by the programmer.

IDENTIFICATION PROGRAMS

DOCUMENTATION

FOR

GENPARM

PROGRAM (SOURCE) FILE NAME IS GENPARM

FILES USED

NAME	DATA DESCRIPTION	IN-OUT
PARAM	Parameter file	OUT

PROGRAM OBJECTIVES

The program GENPARM produces a parameter file for use as input by lake identification system program LAKEID and its associated subroutines.

PROGRAM DESCRIPTION

GENPARM is a FORTRAN timesharing (TSS) program which will prompt the user from any terminal connected with the Honeywell Information System (HIS) computer. The user responses are converted to the format required by LAKEID and written on file PARAM. The FORTRAN called subroutines ATTACH and DETACH are employed to open and close the parameter file.

The prompts ask for information such as the number of tapes used in the scene, the associated scene number, the band number to be processed (4,5,6 or 7) and the threshold required (see documentation for LAKEID for complete description of "threshold"). Default values are zero.

It is imperative that this program be run prior to the LAKEID program.

RUN DIRECTIVES

1. See General Time Sharing Instructions for sign-on instructions.
2. At system "*" level type:

   FRN GENPARM

   The FRN command initiates a FORTRAN run of the program GENPARM. You are now ready to respond to the prompts appropriately.
3. If you have trouble at any time and wish to stop push the BREAK key once - allow a few seconds for processing to cease. A "*" will appear again. At this point you can start over or say "BYE" to end the TSS session.

USER NOTES

1. Tape handling is described in the Tape Handling and Procedures section of the Users Guide.
2. If you can't find your particular problem described in the Problem Section of the User Guide seek assistance from a data processing employee or node supervisor.

PROGRAMMER NOTES

1. The called subroutines ATTACH and DETACH functions may be found in the FORTRAN manual for further description of their functions.

DATA DESCRIPTION FOR FILE PARAM

NAME	DESCRIPTION	FORMAT
ITHRESH	Threshold value	I2
NOTP	Number of tapes in entire scene	I2
ITAPENO	Number of tapes to be used	I2
ISCENEID	Scene ID from Landsat tape	I11
NOSK	Number of image lines to be skipped	I4
IBANDS	Image band to process	I1
IMATRX	Number of arrays to process	I3

DOCUMENTATION
FOR
LAKEID

PROGRAM (SOURCE) FILE NAME IS LAKEID

OBJECT FILE NAME IS LAKEID.O

SUBROUTINES CALLED

SOURCE FILE	OBJECT FILE	FUNCTION
RD9TRK	RD9TRK.O	Read IBM tape record
TAPEID	LAKEID.O	Read tape directory
TAPEHED	LAKEID.O	Read tape header record
TAPEANNO	LAKEID.O	Read tape annotation record
LCALC	LCALC.O	Calculate lake parameters

FILES USED

NAME	DATA DESCRIPTION	IN-OUT
PARAM	Parameter file	IN
LAKES	Master lake file	OUT
CCT	Landsat digital tape	IN

PROGRAM OBJECTIVES

The objective of the FORTRAN program LAKEID is to identify, list and write to a file all information pertaining to lakes collected from Landsat Computer Compatible

Tapes (CCT).

PROGRAM DESCRIPTION

Due to the amount of core storage required by this system of programs, the only feasible way to run and process all information on this particular Honeywell installation is to read several records, 10 if full records are read, into an array and process the array, and store partial lake parameters in table (TAB).

The first task in the program is to read in the parameter file, PARAM (see Data section for full description of file), written by TSS program GENPARM (see Documentation for GENPARM). The parameters are critical, and every effort should be made to insure their accuracy before submitting the job to the system.

The second and all subsequent arrays are processed somewhat differently from the first in that the last line from the previous array is copied to the top zero border line of the succeeding array in order to identify "carry over" lakes and continue their numbering. Once the numbering has been accomplished, the continuation line is zeroed out to provide the top zero border again and processing is resumed.

Once the parameters are accepted to the program, the tape is read by subroutine RD9TRK (see Documentation for

RD9TRK). The directory, header, and annotation records are processed, and all pertinent information is extracted (see Documentation for subroutines TAPEID, TAPEHED, and TAPEANNO).

The lake identification process is to read a set of lines (records) containing pixel values into an array (I) arranging one pixel (byte) per word since Honeywell insists on words. The array is then surrounded by a border of zeros which are necessary during future perimeter calculations. Each word (pixel value) is then systematically compared to the input threshold value to determine if it is land or water. Pixel intensities above the threshold value are considered land, those equal to or below the value are considered water. To date, threshold values tested for the 2 EDIPS tapes examined range from about 7 to 11. Problems arise due to the merging of lakes when higher threshold values are used. A threshold value of 9 provides a fair representation of the aquatic/terrestrial boundry.

If the pixel is determined to be land its value is replaced in the array with a zero. If it is water a temporary sequential lake number is assigned to it which it may or may not keep, depending on whether it is determined to be a separate lake or merges with another pre-defined lake. If merging takes place all the pixels involved take on the lowest lake number, the table of stored lake parameters is searched, and the lake numbers are changed within the table.

After all lake pixels are identified by a unique lake number, a line-printer map of the entire array is printed and the LCALC subroutine is called to produce various calculations and write the information obtained on the master lake file LAKES (see Documentation for subroutine LCALC).

After all processing is complete for that particular array, it is zeroed out in preparation for the next set of values to be stored. This process is repeated as many times as specified on the input parameter file PARAM or until the entire scene has been processed.

RUN DIRECTIVES

1. See General Time Sharing Instructions for sign-on directions.
2. At system "*" level type:

   /RUNLAKE

   RUNLAKE is a command run file which will submit the job to the system. Output will be directed to the state printer in Bunnell.

USER NOTES

1. The TSS program GENPARM must be run prior to running LAKEID.

PROGRAMMER NOTES

1. The coding for LAKEID has been modified considerably since first written.
2. Items passed in COMMON are necessary for subroutines called by subroutine LCALC.

DATA DESCRIPTION FOR FILE PARAM

NAME	DESCRIPTION	FORMAT
ITHRESH	Threshold value	I2
NOTP	Number of tapes in entire scene	I2
ITAPENO	Number of tapes to be used	I2
ISCENEID	Scene ID from Landsat tape	I11
NOSK	Number of image lines to be skipped	I4
IBANDS	Image band to process	I1
IMATRX	Number of arrays to process	I3

DOCUMENTATION

FOR

SUBROUTINE RD9TRK

SUBROUTINE NAME IS RD9TRK

OBJECT FILE NAME IS RD9TRK.O

CALLING PROGRAM IS LAKEID

PARAMETERS PASSED

<u>NUMBER</u>	<u>DESCRIPTION</u>
1	File code of Integer array of at least NWRDS
3	NWRDS - Exact number of words in tape record
4	ERROR FLAG - Returned values are as follows:
	0 - Record read properly
	1 - End of file mark read
	2 - short record (i.e. fewer than NWRDS)
	3 - Physical read error - NWRDS now contains the status word returned by IOS.

Since NWRDS is altered in some cases, it should never be a constant and should be reset before each call. Error processing on the fourth parameter is recommended.

SUBROUTINE DESCRIPTION

RD9TRK is a GMAP subroutine which will read one record from an IBM generated magnetic tape. It is called by the main program of the Identification System, LAKEID, to process the Landsat CCT (see Tape Handling and Procedures).

DOCUMENTATION
FOR
SUBROUTINE TAPEID

SUBROUTINE NAME IS TAPEID

CALLING PROGRAM IS LAKEID

SUBROUTINE DESCRIPTION

The Landsat CCT used in the Identification System of programs has a 90 word directory at the beginning of the first volume. This subroutine calls RD9TRK to read the record into the array IDIRECT for future use if needed.

A second call to RD9TRK reads the EOF and control is returned to LAKEID, the calling program and main program in the system.

DOCUMENTATION

FOR

SUBROUTINE TAPEHED

SUBROUTINE NAME IS TAPEHED

CALLING PROGRAM IS LAKEID

SUBROUTINE DESCRIPTION

The Landsat CCT used by the Identification System has a header record on the first volume. This subroutine is called by LAKEID to extract information from the header record and store it.

RD9TRK is called to read the header record into array IHEADER. Bytes 111 and 112 are extracted from word 28 through an OR function using left shift and right rotations to manipulate bits (see ALGORITHM for details) and eliminate the sign bit. The image record length is stored in "NUMB" and the number of pixels is extracted from word 33, byte 131 and 132 and stored in "NPIX". Control is returned to LAKEID.

ALGORITHM

TAPEHED takes a four byte word and zeros out the left two bytes (half-word). The third byte is moved one bit to the right since IBM uses 8 bit bytes and Honeywell uses 9.

DOCUMENTATION
FOR
SUBROUTINE TAPEANNO

SUBROUTINE NAME IS TAPEANNO

CALLING PROGRAM IS LAKEID

SUBROUTINE DESCRIPTION

This subroutine is particularly important to the Identification System since it processes the annotation record off of the Landsat CCT. RD9TRK is called to read the record (see Tape Handling and Procedures).

The programmer will soon realize, after reading the documentation provided in the Tape Handling and Procedures Section of this documentation, that the tick mark data provided in the annotation record is stored in a very strange and confusing manner with the location stored in binary and the coordinate data stored in ASCII. The first bit tells the storage pattern of the coordinate data with respect to the location. The storage may either be three spaces between the location and the coordinate or the location immediately followed by the coordinate and then three spaces. There is zero fill after each set of tick marks, and the left and right side tick marks are divided into two sets each with zero fill between sets.

The process of extracting the data required involves reading the annotation into array IHEADER, and then using the DECODE function on words 9 and 10 to obtain path and row. Tick mark information extraction requires two basic functions involving left shifts and right rotations of the bits. Once the information is extracted it is stored in four separate arrays. The subroutine PIXGEO and its called subroutines dictate the method for array storage and utilize the arrays for derivation of the latitude and longitude coordinates.

DOCUMENTATION

FOR

SUBROUTINE LCALC

PROGRAM (SOURCE) FILE NAME IS LCALC

OBJECT FILE NAME IS LCALC.O

CALLING PROGRAM IS LAKEID

PARAMETERS PASSED

NAME	DESCRIPTION
I	Pixel array
LINDEX	Line number index
NLAKE	Array of lake numbers
IMATRX	Number of arrays to process

SUBROUTINES CALLED

SOURCE FILE	OBJECT FILE	FUNCTION
IDENT	IDENT.O	Latitude & Longitude Subroutines

FILES USED

NAME	DATA DESCRIPTION	IN-OUT
LAKES	Master lake file	OUT

PROGRAM OBJECTIVES

The subroutine LCALC is called by program LAKEID to calculate area, perimeter, centroid and crenulation of the lakes identified by LAKEID and to call subroutines to determine the latitude and longitude of the lake's centroid.

PROGRAM DESCRIPTION

The calling program, LAKEID, establishes an array of pixel samples which is passed as an argument when the LCALC subroutine is called (see Documentation for LAKEID). The identification process handles one array at a time, and there is a good chance that several lakes will not be fully contained in the array.

These lakes are considered "carry-over" and are written to a table called TAB. All lakes which touch the east or west borders of the array are eliminated. On the first array the north border lakes are written to table TAB and flagged as north border, and although they may be finally contained in a subsequent array, they will be eliminated by virtue of the fact that initially they had a north touching border; hence, the calculations are incomplete for them.

All calculations (see ALGORITHMS) for lakes with south touching borders on the first array and all subsequent arrays, and lakes with both north and south borders for all subsequent arrays are stored in TAB.

The program identifies a lake as complete if it touches the south border of the previous array and does not continue in the present array or if it terminates prior to reaching the south border of the present array. Upon completion, all calculations are performed and the table (TAB) is searched for this lake's data from previous arrays. Parameters from TAB are combined with the parameters from the array which completes the lake.

Subroutines on file IDENT (see Identification System Flowchart and documentation for subroutine PIXGEO) are called to establish the latitude and longitude for the coordinates of the lake centroid. The calculations are then written to file LAKES along with the latitude and longitude of the lake centroid scene number, zone and quad (see TABLE DESCRIPTION for file table TAB description).

ALGORITHMS

AREA

1 pixel sample = .00325 sq. km. of land.

Lake pixel samples are detected by systematic scan of an array wherein the total number of pixels assigned a particular lake number is calculated and the result is multiplied by .00325 to obtain the total area in sq. km.

PERIMETER

1 pixel sample = area 57 X 57 km.

The first lake sample is detected and labelled as starting sample. Through an intricate and time consuming method of comparison to neighbor pixel samples a perimeter is calculated. The values added depend on the direction of movement from sample to sample as one progresses around the perimeter of the lake and arrives back at the beginning sample. If movement is horizontal or vertical 57 is added. If movement is diagonal (consequently accross the hypotenuse of the right triangle) 80.6 is added.

CRENULATION

CRENULATION = PERIMETER / SQRT (4PI * AREA)

Comparison of lake perimeter with perimeter (P2) of an imaginary circular lake of equal area and smooth shore.

CENTROID

X/N, where X is sum of X-coordinates, N is total points

Y/N, where Y is sum of Y-coordinates, N is total points

Each pixel is identified by its row (x-coordinate) and sample (y-coordinate) position within the array. The total of the sample values is divided by the total number of pixels in the lake to arrive at the horizontal coordinate placement. The total of all the row values is divided by the total number of pixels in the lake to obtain the vertical coordinate placement.

DESCRIPTION FOR TABLE TAB

ELEMENT NUMBER	DESCRIPTION
1	Lake index
2	Area
3	Perimeter
4	Centroid counter HICT
5	Centroid counter HPNT
6	Centroid counter VICT
7	Centroid counter VPNT
8	North border on first array flag
9	South border on previous array flag

DATA DESCRIPTION FOR FILE LAKES .

NAME	DESCRIPTION
ZONE	Geographic zone
QUAD	Geographic quad from USGS MAPS
LATITUDE	Latitude of centroid
LONGITUDE	Longitude of centroid
LDEX	Lake number
AREA	Computer calculated area
PERIMETER	Computer calculated perimeter
CRENULATION	Computer calculated crenulation
SCENE	Scene number from CCT

PROGRAMMER NOTES

1. The coding for LCALC has been modified considerably since first written.
2. Items passed in COMMON are necessary for subroutines in source file IDENT which calculate the latitude and longitude of the centroid of each lake identified.

DOCUMENTATION

FOR

SUBROUTINE PIXGEO

PROGRAM (SOURCE) FILE NAME IS IDENT

OBJECT FILE NAME IS IDENT.O

CALLING PROGRAM IS LCALC

SUBROUTINES CALLED

NAME	DESCRIPTION OR FUNCTION
UTM	Universal Transverse Mercator Projection
CZONE	Calculates HOM zone from row number
CORNER	Calculates projection coordinates for corners
BILINE	Bilinear interpolation for centroid
HOTINE	Hotine Oblique Mercator Transformation
C1866	Sets eccentricity and major axis
OTMFWD	Calculates HOM linear coordinate values
OTMGEN	Generates elements of HOM projection

PROGRAM OBJECTIVES

The objectives of the major subroutine PIXGEO and all of the subroutines called by PIXGEO is to establish a unique latitude and longitude for the centroid of the lake identified by the main Identification System program LAKEID and its called subroutine LCALC.

PROGRAM DESCRIPTION

PIXGEO is a subroutine called by the subroutine LCALC to geodetically register pixels for use with Landsat Digital HOM or UTM projected imagery. PIXGEO in turn calls subroutines to perform various calculations and establish certain parameters to ultimately derive a latitude and longitude for the line and sample location coordinates for the centroid of each lake identified by program LAKEID.

All subroutines are written in FORTRAN and use the tick mark information found in the annotation record of the original Landsat CCT (see Documentation for LAKEID and subroutine TAPEANNO and Tape Handling and Procedures for further tick mark information).

The method employed is to calculate rectangular coordinates (HOM or UTM) at the four corner points of the CCT image which are defined as the intersections of lines and samples containing tick marks. Bilinear interpolation using the pixel and rectangular coordinates at the corner points can calculate rectangular coordinates for any point within the image.

The subroutines used to calculate the transformations between geodetic and rectangular coordinates are UTM and HOM. HOM was used for this particular application because the area under consideration lies above 65 degrees north latitude. At present UTM is a special EROS Data Center product as HOM is the primary product no matter what the latitude of a Landsat scene; however, the UTM projection is not as accurate as the HOM projection above 65 degrees north latitude.

PROGRAMMER NOTES:

1. The documentation for the subroutines described here is far too extensive to adequately cover in this manual.
   It is therefore strongly recommended that any programmer intending to use this set of subroutines read the source files and associated documentation carefully before proceeding.

DOCUMENTATION
FOR
UPLAKE

PROGRAM (SOURCE) FILE NAME IS UPLAKE

OBJECT FILE NAME IS UPLAKE.O

FILES USED

NAME	DATA DESCRIPTION	IN-OUT
CARDS	Updates for lake file	IN
LAKES	Master Lake File	IN
LAKES	Master Lake File	OUT

PROGRAM OBJECTIVES

UPLAKE is required to append individual lake records in the master lake file with information gathered from external sources, such as field studies.

PROGRAM DESCRIPTION

The Identification System main program LAKEID identifies lakes by using Landsat CCT's, and uniquely defines them by the latitude and longitude of their centroid. The latitude and longitude is written, along with various parameters obtained from computer calculations, as a record to a file. Each lake is described in one record only (see Documentation for LAKEID for data description).

Since this file of lake records is meant to be a complete data base for the Retrieval System of programs, a method of appending each lake record with auxiliary information was developed using an "updating" procedure.

The program UPLAKE, written in COBOL, was designed to process a file containing records which are keyed to match the records on the master file by unique latitude and longitude in decimal degrees. It is therefore critical that the latitude and longitude key used on the update records identically match the key on the master file used as input to the program. This information can be obtained from a previous listing of the file in key order. When a match is made, all information contained on the update record is transferred to the matching lake record and the entire record is listed on output with all changes and additions exactly as they appear on the file.

RUN DIRECTIVES

1. See General Time Sharing Instructions for sign-on directions.

2. If all is in order at system "*" level type:

   /RUNUP

   Your job will be submitted to the system for execution and your output will be directed to the state printer in the Bunnell Building.

3. After the prompt "*" type:

   BYE

   This will end your time sharing session.

DATA DESCRIPTION FOR FILE LAKES

FIELD	FORMAT
LOCATION	PIC 9
QUAD	PIC X(3)
LATITUDE	PIC S9(2)V9(5)
DIRECTION	PIC X
LONGITUDE	PIC S9(3)V9(5)
DIRECTION	PIC X
AREA	PIC 9(4)V9(5)
PERIMETER	PIC 9(5)V9(3)
CRENULATION	PIC 9(4)V9(3)
SCENE	PIC X(11)
STRIP	PIC 9(3)
LINE	PIC 9(4)
LAKE	PIC X(4)
AREA-FREE-WATER	PIC 9(3)V9(5)
AREA-FREE-WATER-DATE	PIC 9(6)
DEPTH	PIC 9(3)V9
DEPTH-DATE	PIC 9(6)
INLET	PIC X
OUTLET	PIC X
SUBST-NMB	PIC 99 COMP-1
SUBSTRATE	PIC X(2) OCCURS 1 TO 5 TIMES DEPENDING ON SUBST-NMB
CONDUCTIVITY	PIC 9(6)
CONDUCTIVITY-DATE	PIC X(6)

VECTORS	PIC X(6)
CLASSIFICATION-NMB	PIC 99 COMP-1
CLASSIFICATION-S	PIC X(2) OCCURS 1 TO 5 TIMES DEPENDING ON CLASS-NMB
REFERENCES	PIC X
FISH-NMB2	PIC 99 COMP-1
FISH-CODE	PIC XX OCCURS 1 TO 10 TIMES DEPENDING ON FISH-NMB2
FISH-DATE	PIC X(6)
ACTIVITY	PIC X
ACTIVITY-NMB2	PIC 99 COMP-1
ACTIVITY-TYPE	PIC XX OCCURS 1 TO 5 TIMES DEPENDING ON ACT-NMB2
VEG-NMB2	PIC 99 COMP-1
VEG-CODE	PIC XX OCCURS 1 TO 10 TIMES DEPENDING ON VEG-NMB2
PERCENT-COVERED	PIC XXX
VEGETATION-DATE	PIC X(6)
VERIFIED-AREA	PIC 9(3)V9(5)
VERIFIED-AREA-DATE	PIC 9(6)
NAME	PIC X(10)

USER NOTES

The updating procedure is a critical function and should be handled with extreme caution since valuable information could be lost permanently due to carelessness. It should also be stressed that no one should attempt to run the update program unless they have read the documentation for the program UPLAKE completely. Details for the completion of update forms are included in the section FORMS.

PROGRAMMER NOTES

The master file is sorted on ascending 17-digit key. These are in decimal degrees accurate to 5 decimal places each (see DATA DESCRIPTION). The update file is sorted in the same manner.

The master lake file contains variable length records which are expanded when released to the sort and compressed when written back to the file to conserve space.

UPDATE PROCEDURES

1. Fill out provided update sheets and have them keyed onto file CARDS.
2. Once the updates are on file CARDS check to insure that the input and output lake files are correct.

FORMS

Due to the precision demanded by the updating process, forms are provided to help the user.

The following is field-by-field description of the form. Any field except the key and update type may be left blank. The default is no change to the file. The program will add to or replace old information on the lake file with the new information supplied by the user via the forms. It is therefore essential that care be taken when completing the forms to avoid error in the lake key or data fields. Only the update type with any changes to be made need be submitted to the update program.

MASTER LAKE FILE UPDATES

KEY

TYPE 1

DEPTH

DATE

FREE WATER AREA

DATE

INLET

OUTLET

SUBSTRATE

CONDUCTIVITY

DATE

CLASSIFICATION

TYPE 2

FISH

DATE

ACTIVITY

ACTIVITY PRESENT

REFERENCES

TYPE 3

VEGETATION

DATE

PERCENT COVERAGE

VERIFIED AREA

DATE

NAME

UPDATE TYPE 1

FIELD	COLS.	DESCRIPTION	TYPE N=NUM A=ALPHA
TYPE	1	Update type	N
KEY	2-18	17-digit latitude/longitude 5-decimal places do not use decimal in code	
	2-8	Latitude	N
	9	Lat. direction	A
	10-17	Longitude	N
	18	Long. direction	A
DEPTH	23-28	Depth date (DDMMYY)	N
AREA	29-36	Free water below ice	N
DATE	37-42	Free water date (DDMMYY)	N
INLET	43	Inlet present (Y OR N)	A
OUTLET	44	Outlet present (Y OR N)	A
SUBSTRATE	45-54	5 sets of 2 (see SUBSTRATE description)	A
CONDUCTIVITY	55-60	Conductivity	N
DATE	61-66	Conductivity date (DDMMYY)	N
CLASSIFICATION	67-76	5 sets of 2 (see CLASSIFICATION description)	A

UPDATE TYPE 2

FIELD	COLS.	DESCRIPTION	TYPE N=NUM A=ALPHA
TYPE	1	Update type	N
KEY	2-18	17-Digit latitude/longitude 5-decimal places do not use decimal in code	
	2-8	Latitude	N
	9	Lat. direction	A
	10-17	Longitude	N
	18	Long. direction	A
FISH	19-38	10 sets of 2 (see FISH description)	A
DATE	39-44	Fish date (DDMMYY)	N
ACTIVITY	45-54	5 sets of 2 (see ACTIVITY CODES description)	A
ACTIVITY	55	Activity present (Y OR N)	A
REFERENCES	56	References on file (Y OR N)	A

UPDATE TYPE 3

FIELD	COLS.	DESCRIPTION	TYPE N=NUM A=ALPHA
TYPE	1	Update type	N
KEY	2-18	17-Digit latitude/longitude 5-decimal places Do not ude decimal in code	
	2-8	Latitude	N
	9	Lat. Direction	A
	10-17	Longitude	N
	18	Long. direction	A
VEGETATION	19-38	10 sets of 2 (see VEGETATION description)	A
DATE	39-44	Vegetation date (DDMMYY)	N
PERCENT	45-47	Percent vegetation cover	N
AREA	48-55	Verified area	N
DATE	56-61	Area date (DDMMYY)	N
NAME	62-71	Lake name	A

CLASSIFICATION

M		Marine
E		Estuarine
R		Riverine
L		Lacustrine
	LO	Oxbow
	LT	Thaw & others
P		Palustrine

SUBSTRATE

R		Rock
	RB	Bedrock
	RR	Rubble
U		Unconsolidated
	UG	Cobble-gravel
	US	Sand
	UM	Mud
	UO	Organic
V		Aquatic bed (Vegetation)
	VA	Algal
	VM	Moss (aquatic)
	VV	Vascular

VEGETATION (hydrophytes)

A		Algae (benthic)
L		Lichens
M		Mosses
V		Vascular plants (unidentified)
	N	None
	AF	Arctophila fulva (pendent grass)
	CA	Carex aquatilis (sedge)
	DF	Dupontia fisheri (tundra grass)
	EA	Eriophorum angustifolium (cotton grass)
	ER	Eriophorum russeolum
	ES	Eriophorum scheuchzeri
	SF	Saxifraga foliolasa
	SR	Saxifraga rivularis
	RP	Ranunculus pallasii (buttercups)
	RG	Ranunculus gmelini
	RH	Ranunculus hyperboreus
	RN	Ranunculus nivalis
	EQ	Equisetum sp. (horsetail)
	HV	Hippuris vulgaris (mare's tail)
	PP	Potentilla polustris (march fine finger)
	AA	Alopecurus alpinus (alpine foxtail)
	CP	Cardaminine protensis angustifolia
	PV	Potamogeton vaginatus (pondweed)
	CT	Chrysasplenium tetrandrum
	PF	Petasites frigidus

AL	*Arctagrostis latifolia*
JB	*Juncus biglumis*
HP	*Hierochloe pauciflora* (Holy Grass)

ACTIVITY CODES

Human Proximity & Use for:

subsistance or non-monetary/commercial gain

HS - seasonal use

HY - year-round population

Oil & Gas

OE - exploration drilling or past use

OD - development or present use

Mining (i.e. gravel, coal, etc.)

ME - exploration or past use

MD - development or present use

Special Area Designation (set aside for research, waterfowl protection, etc.)

SA

Water Withdrawal or Waste Disposal

WI - industry

WV - village

RE - recreation

OT - other

NO - none

FISH CODES

N	None	
AL	Arctic lamprey	Lampetra japonica (Martens)
AC	Arctic cisco	Coregonus autumnalis (Pallas)
BC	Bering cisco	Coregonus laurettae Bean
BW	Broad whitefish	Coregonus nasus (Pallas)
HW	Humpback whitefish	Coregonus pidschian (Gmelin)
LC	Least cicso	Coregonus sardinella Valenciennes
PS	Pink salmon	Oncorhyncus gorbuscha (Walbaum)
CS	Chum salmon	Oncorhyncus keta (Walbaum)
RW	Round whitefish	Prosopium cylindraceum (Pallas)
CH	Arctic char	Salvelinus alpinus (Linnaeus)
LT	Lake trout	Salvelinus namaycush (Walbaum)
IN	Inconnu	Stenodus leucichthys (Guldenstadt)
GR	Arctic grayling	Thymallus arcticus (Pallas)
RS	Rainbow smelt	Osmerus mordax Mitchell
PS	Pond smelt	Hypomesus olidus Pallas
AB	Alaska blackfish	Dallia pectoralis Bean
NP	Northern pike	Esox lucius Linnaeus
LS	Longnose sucker	Catostomus catostomus (Forster)
BU	Burbot	Lota lota (Linnaeus)
NS	Ninespine stickleback	Pungitius pungitius (Linnaeus)
SS	Slimy sculpin	Cottus cognatus Richardson
FS	Fourhorn sculpin	Myoxocephalus quadricornis Linnaeus
AF	Arctic flounder	Liopsetta glacialis Pallas
SF	Starry flounder	Platichthys stellatus Pallas

RETRIEVAL PROGRAMS

DOCUMENTATION

FOR

GENRET

PROGRAM (SOURCE) FILE NAME IS GENRET

FILES USED

NAME	DATA DESCRIPTION	IN-OUT
RET	Parameter file	OUT

PROGRAM OBJECTIVES

The program GENRET produces a parameter file for use as input by lake retrieval system program RETRIEV and its associated subroutines.

PROGRAM DESCRIPTION

GENRET is a FORTRAN time sharing (TSS) program which will prompt the user from any terminal connected with the Honeywell Information System (HIS) computer. The user responses are converted to the format required by RETRIEV and written on file RET. The FORTRAN called subroutines ATTACH and DETACH are employed to open and close the parameter file.

DATA DESCRIPTION FOR FILE RET

NAME	DESCRIPTION
REPORT TYPE	Sorted output = "1" Catalog and restricted = "2"
QUAD	Flag for quad restriction
LATITUDE	Latitude for northeast quad corner
LONGITUDE	Longitude for northeast quad corner
LATITUDE	Latitude for southwest corner
LONGITUDE	Longitude for southwest corner
CATALOG FLAG	Flag for list by descending key
AREA FLAG	">" "<" or "="
AREA	Calculated area
DEPTH FLAG	">" "<" or "="
DEPTH	Depth
FREE AREA FLAG	">" "<" or "="
FREE AREA	Free area
CONDUCTIVITY FLAG	">" "<" or "="
CONDUCTIVITY	Conductivity
FISH FLAG	">" "<" or "="
FISH	Fish
VEGETATION FLAG	">" "<" or "="
VEGETATION	Vegetation
OUTLET FLAG	">" "<" or "="
OUTLET	Outlet
INLET FLAG	">" "<" or "="
INLET	Inlet

SORT FIELD Name or field (i.e. area,depth etc.)

RUN DIRECTIVES

1. See General Time Sharing Instructions for sign-on directions.
2. At system "*" level type:

   /LISTLAKE

   LISTLAKE is a controlled run which will run the program GENRET and submit the program RETRIEV to the system to be run. Output will be directed to the state printer in BUNNELL.

   If at any time you wish to stop push the "BREAK" key once - allow a few seconds for processing to complete - a "*" should appear.

   At this time you may either repeat the process or type "BYE" to terminate the TSS session.

USER NOTES

1. This TSS program must be run prior to the RETRIEV program.
2. Since all terminal responses will be directives to the program and therefore dictate which output you will receive it is important to read all input directions before responding.

PROGRAMMER NOTES

1. The ATTACH and DETACH functions may be found in the FORTRAN manual for further description of their functions.

DOCUMENTATION

FOR

RETRIEV

PROGRAM (SOURCE) FILE NAME IS RETRIEV

OBJECT FILE NAME IS RETRIEV.O

SUBROUTINES CALLED

SOURCE FILE	OBJECT FILE	FUNCTION
ARCALC	ARCALC.O	Calculate quad area

FILES USED

NAME	DATA DESCRIPTION	IN-OUT
RET	Parameter file	IN
LAKES	Master lake file	IN
REFER	References	IN

PROGRAM OBJECTIVES

The program RETRIEV is the main program in the Retrieval System. Its function is to produce various listing from the master lake file (LAKES) created by the Identification System (see documentation for Identification System).

PROGRAM DESCRIPTION

The Identification System is responsible for identifying lakes from Landsat CCT's, calculating various parameters for each lake, listing the lakes and associated parameters and establishing a master file of lakes called LAKES. The Retrieval System was developed to list the master lake file according to a specific set of instructions or directives. These directives are provided by the file RET which is the product of a TSS program GENRET (see documentation for GENRET).

The first task performed by RETRIEV is to read the directive file RET and proceed accordingly (see DATA DESCRIPTION).

A report type code of "1" indicates that a sorted output is requested. The next directive checked at this point is the field on which the file is to be sorted. The sorted file is then listed.

If the report type code is "2" a sieving technique will take place wherein listings may be restricted by parameters held in the directive file. These parameters take the form of a value and an associated logical comparator (i.e. ">", "<", or "="). If the comparator is missing the field is ignored. Only those lakes which meet all the provided specifications are listed on output.

One of the most critical restrictions allowed is by latitude and longitude. A geographic quad may be defined by specifying the northeast and southwest corners in terms of latitude and longitude. Only lakes whose centroid lies within the resulting quad may be further checked and restricted by the remaining fields, all other lakes are eliminated immediately. The latitude and longitude input are in degrees and minutes accurate to one decimal place. A calculation is performed to obtain decimal degrees to an accuracy of 5 decimal places for each. Once the quad is established a subroutine (ARCALC) is called to calculate the total area defined by the quad (see documentation for ARCALC).

The sieving process first checks the quad to be considered if requested. Next, there is a systematic process of elimination for any flagged field. The flag in this case is the logical comparator. The final output is a list of all lakes on the master file which fit the provided criterion.

A file of references is available which contains any references pertaining to the lakes held on the master lake file. The reference records are in order by ascending lake key. This file is matched against the individual lake to be listed. If a match is made the references are listed after the lake to which they refer.

A flag field is checked which indicates if a catalog listing is desired. This is a list of the entire file in order by descending latitude, longitude key. It is an ideal reference for the user to determine future listing sieve limits and sort parameters. The catalog is not available if the report type is 1 since the sorted output from this report type includes the entire file without restrictions.

RUN DIRECTIVES

1. See General Time Sharing Instructions for sign-on directions.

6. At system "*" level type:

   /LISTLAKE

   LISTLAKE is a command run file which will submit the job to the system. Output will be directed to the state printer in Bunnell.

DATA DESCRIPTION FOR FILE RET

NAME	DESCRIPTION
REPORT TYPE	Sorted output = "1" Catalog and restricted = "2"
QUAD	Flag for quad restriction
LATITUDE	Latitude for northeast quad corner
LONGITUDE	Longitude for northeast quad corner
LATITUDE	Latitude for southwest corner
LONGITUDE	Longitude for southwest corner
CATALOG FLAG	Flag for list by descending key
AREA FLAG	">" "<" or "="
AREA	Calculated area
DEPTH FLAG	">" "<" or "="
DEPTH	Depth
FREE AREA FLAG	">" "<" or "="
FREE AREA	Free area
CONDUCTIVITY FLAG	">" "<" or "="
CONDUCTIVITY	Conductivity
FISH FLAG	">" "<" or "="
FISH	Fish
VEGETATION FLAG	">" "<" or "="
VEGETATION	Vegetation
OUTLET FLAG	">" "<" or "="
OUTLET	Outlet
INLET FLAG	">" "<" or "="
INLET	Inlet

SORT FIELD   Name or field (i.e.area depth etc.)

USER NOTES

1. The TSS program GENRET must be run prior to running LISTLAKE.

PROGRAMMER NOTES

1. The records on the master lake file are variable length and should be treated accordingly. A file description for the master lake file is included in the documentation for the program LAKEID.

DOCUMENTATION
FOR
SUBROUTINE ARCALC

PROGRAM (SOURCE) FILE NAME IS ARCALC

OBJECT FILE NAME IS ARCALC.O

CALLING PROGRAM IS RETRIEV

PARAMETERS PASSED

NAME	DESCRIPTION
DLAT1	Northeast corner latitude
DLAT2	Southwest corner latitude
DLON1	Southwest corner longitude
DLON2	Northeast corner longitude

PROGRAM OBJECTIVES

The subroutine ARCALC is called by program RETRIEV to calculate the area of the geographic quad designated by the parameter file RET.

PROGRAM DESCRIPTION

ARCALC is a FORTRAN subroutine called by the main Retrieval System program RETRIEV to calculate the area of the geographic quad established by the corner points given in the parameter and directive file RET. These corner points, the northeast and southwest coordinates, are input as degrees and minutes accurate to one decimal place. They are converted to decimal degrees accurate to 5 decimal places and are passed as parameters in the call statement to the subroutine.

The input parameters are converted from degrees to radians. The calculation is performed (see ALGORITHM) and the area in sq. km. is returned to the called program as a passed parameter. The area is accurate to 5 decimal places and is stored as COMP-2 in the working storage section of the program. COMP-2 is required for all parameters passed between a COBOL calling program and a FORTRAN subroutine.

ALGORITHM:

```
AREA = 6364**2 * (SIN(DLAT1) - SIN(DLAT2)) * (DLON1-DLON2)
```

where:

6364 = radius of the earth in km.